A 60-person Federal Advisory Committee (The "National Climate Assessment and Development Advisory Committee" or NCADAC) has overseen the development of this report.

The NCADAC, whose members are listed below, was established under the Department of Commerce in December 2010 and is supported through the National Oceanic and Atmospheric Administration (NOAA). It is a federal advisory committee established as per the Federal Advisory Committee Act of 1972. The Committee serves to oversee the activities of the National Climate Assessment. Its members are diverse in background, expertise, geography and sector of employment.

The NCADAC engaged more than 240 authors in the creation of the report. The authors are acknowledged at the beginning of the chapters they co-authored.

Following extensive review by the National Academies of Sciences and by the public, this report will be revised by the NCADAC and will then be submitted to the Federal Government for consideration in the Third National Climate Assessment Report.

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Climate Change and the American People

Climate change, once considered an issue for a distant future, has moved firmly into the present. This report of the National Climate Assessment and Development Advisory Committee concludes that the evidence for a changing climate has strengthened considerably since the last National Climate Assessment report, written in 2009. Many more impacts of human-caused climate change have now been observed. Corn producers in Iowa, oyster growers in Washington State, and maple syrup producers in Vermont have observed changes in their local climate that are outside of their experience. So, too, have coastal planners from Florida to Maine, water managers in the arid Southwest and parts of the Southeast, and Native Americans on tribal lands across the nation.

Americans are noticing changes all around them. Summers are longer and hotter, and periods of extreme heat last longer than any living American has ever experienced. Winters are generally shorter and warmer. Rain comes in heavier downpours, though in many regions there are longer dry spells in between.

Other changes are even more dramatic. Residents of some coastal cities see their streets flood more regularly during storms and high tides. Inland cities near large rivers also experience more flooding, especially in the Midwest and Northeast. Hotter and drier weather and earlier snow melt mean that wildfires in the West start earlier in the year, last later into the fall, threaten more homes, cause more evacuations, and burn more acreage. In Alaska, the summer sea ice that once protected the coasts has receded, and fall storms now cause more erosion and damage that is severe enough that some communities are already facing relocation.

Scientists studying climate change confirm that these observations are consistent with Earth's climatic trends. Long-term, independent records from weather stations, satellites, ocean buoys, tide gauges, and many other data sources all confirm the fact that our nation, like the rest of the world, is warming, precipitation patterns are changing, sea level is rising, and some types of extreme weather events are increasing. These and other observed climatic changes are having wide-ranging impacts in every region of our country and most sectors of our economy. Some of these changes can be beneficial, such as longer growing seasons in many regions and a longer shipping season on the Great Lakes. But many more have already proven to be detrimental, largely because society and its infrastructure were designed for the climate of the past, not for the rapidly changing climate of the present or the future.

This National Climate Assessment collects, integrates, and assesses observations and research from around the country, helping to show what is actually happening and what it means for peoples' lives, livelihoods, and future. This report includes analyses of impacts on seven selected sectors: human health, water, energy, transportation, agriculture, forests, and ecosystems and biodiversity. This report additionally focuses on the interactions among several sectors at the national level. It also assesses key impacts on the regions of the U.S.: Northeast, Southeast and Caribbean, Midwest, Great Plains, Southwest, Northwest, Alaska and the Arctic, Hawai'i and the Pacific Islands; as well as coastal areas, oceans, and marine resources. Finally, this report is the first to explicitly assess the current state of adaptation, mitigation, and decision support activities.

Climate change presents a major challenge for society. This report and the sustained assessment process that is being developed represent steps forward in advancing our understanding of that challenge and its far-reaching implications for our nation and the world.

The National Climate Assessment and Development Advisory Committee

Jerry Melillo, Chair

Terese Neu Richmond, Vice Chair

Gary Yohe, Vice Chair

Executive Summary

Climate change is already affecting the American people. Certain types of weather events have become more frequent and/or intense, including heat waves, heavy downpours, and, in some regions, floods and droughts. Sea level is rising, oceans are becoming more acidic, and glaciers and arctic sea ice are melting. These changes are part of the pattern of global climate change, which is primarily driven by human activity.

Many impacts associated with these changes are important to Americans' health and livelihoods and the ecosystems that sustain us. These impacts are the subject of this report. The impacts are often most significant for communities that already face economic or health-related challenges, and for species and habitats that are already facing other pressures. While some changes will bring potential benefits, such as longer growing seasons, many will be disruptive to society because our institutions and infrastructure have been designed for the relatively stable climate of the past, not the changing one of the present and future. Similarly, the natural ecosystems that sustain us will be challenged by changing conditions. Using scientific information to prepare for these changes in advance provides economic opportunities, and proactively managing the risks will reduce costs over time.

Evidence for climate change abounds, from the top of the atmosphere to the depths of the oceans. This evidence has been compiled by scientists and engineers from around the world, using satellites, weather balloons, thermometers, buoys, and other observing systems. The sum total of this evidence tells an unambiguous story: the planet is warming.

U.S. average temperature has increased by about 1.5°F since 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's hottest on record. Though most regions of the U.S. are experiencing warming, the changes in temperature are not uniform. In general, temperatures are rising more quickly at higher latitudes, but there is considerable observed variability across the regions of the U.S.

U.S. temperatures will continue to rise, with the next few decades projected to see another 2°F to 4°F of warming in most areas. The amount of warming by the end of the century is projected to correspond closely to the cumulative global emissions of greenhouse gases up to that time: roughly 3°F to 5°F under a lower emissions scenario involving substantial reductions in emissions after 2050 (referred to as the "B1 scenario"), and 5°F to 10°F for a higher emissions scenario assuming continued increases in emissions (referred to as the "A2 scenario") (Ch. 2).

The chances of record-breaking high temperature extremes will continue to increase as the climate continues to change. There has been an increasing trend in persistently high nighttime temperatures, which have widespread impacts because people and livestock get no respite from the heat. In other places, prolonged periods of record high temperatures associated with droughts contribute to conditions that are driving larger and more frequent wildfires. There is strong evidence to indicate that human influence on the climate has already roughly doubled the probability of extreme heat events like the record-breaking summer of 2011 in Texas and Oklahoma (Ch. 2,3,6,9,20).

Human-induced climate change means much more than just hotter weather. Increases in ocean and freshwater temperatures, frost-free days, and heavy downpours have all been documented. Sea level has risen, and there have been large reductions in snow-cover extent, glaciers, permafrost, and sea ice. Winter storms along the west coast and the coast of New England have increased slightly in frequency and intensity. These changes and other climatic changes have affected and will continue to affect human health, water supply, agriculture, transportation, energy, and many other aspects of society (Ch. 2,3,4,5,6,10,12,16,20,24,25).

Some of the changes discussed in this report are common to many regions. For example, very heavy precipitation has increased over the past century in many parts of the country. The largest increases have occurred in the Northeast, Midwest, and Great Plains, where heavy downpours have exceeded the capacity of infrastructure such as storm drains, and have led to flooding events and accelerated erosion. Other impacts, such as those associated with the rapid thawing of permafrost in Alaska, are unique to one U.S. region (Ch. 2,16,18,19,20,21,22,23).

Some impacts that occur in one region have more wide-ranging effects. For example, the dramatic decline of summer sea ice in the Arctic – a loss of ice cover roughly equal to half of the continental U.S. – exacerbates global warming by reducing the reflectivity of Earth's surface and increasing the amount of heat the Arctic absorbs. There is some evidence that this affects weather patterns farther south in the United States. Similarly, wildfires in one region can trigger poor air quality in far-away regions, and new evidence suggests the particulate matter in the atmosphere affects global circulation, leading to more persistent periods of anomalous weather. Major storms that hit the Gulf Coast affect the entire country through their cascading effects on oil and gas production and distribution (Ch. 2,4,16,17,18,19,20,22).

Sea level rise, combined with coastal storms, has increased the risk of erosion, storm-surge damage, and flooding for coastal communities, especially along the Gulf of Mexico, the Atlantic seaboard, and Alaska. In the Southeast, coastal infrastructure including roads, rail lines, energy infrastructure, and port facilities including naval bases, are at risk from storm surge that is exacerbated by rising sea level. Over the past century, global sea level has risen by about 8 inches. Since 1992, the rate of global sea level rise measured by satellites has been roughly twice the rate observed over the last century. Sea level is projected to rise by another 1 to 4 feet in this century. A wider range of scenarios, ranging from 8 inches to 6.6 feet of rise by 2100, has been suggested for use in risk-based analyses. In general, higher emissions scenarios that lead to more warming would be expected to lead to sea level rise toward the upper end of the projected range. The stakes are high, as nearly five million Americans live within four feet of the local high-tide level (Ch. 2,4,10,16,17,20, 22,25).

In addition to changing climate, carbon dioxide from fossil fuel burning has a direct effect on the world's oceans. Carbon dioxide interacts with ocean water to form carbonic acid, lowering the ocean's pH. Ocean surface waters have become 30% more acidic as they have absorbed large amounts of carbon dioxide from the atmosphere. This ocean acidification reduces the capacity of marine organisms with shells or skeletons made of calcium carbonate (such as corals, krill, oysters, clams, and crabs) to survive, grow, and reproduce, which in turn will affect the entire marine food chain (Ch. 2,8,23,24,25).

Climate change produces a variety of stresses on society, affecting human health, natural ecosystems, built environments, and existing social, institutional, and legal agreements. These stresses interact with each other and with other non-climate stresses, such as habitat fragmentation, pollution, increased consumption patterns, and biodiversity loss. Addressing these multiple stresses requires the assessment of composite threats as well as tradeoffs among the costs, benefits, and risks of available response options (Ch. 3,5,8,9,10,11,14,16,19,20,25,26,27,28).

Climate change will influence human health in many ways; some existing health threats will intensify, and new health threats will emerge. Some of the key drivers of health impacts include: increasingly frequent and intense extreme heat, which causes heat-related illnesses and deaths and over time, worsens drought and wildfire risks, and intensifies air pollution; increasingly frequent extreme precipitation and associated flooding that can lead to injuries and increases in marine and freshwater-borne disease; and rising sea levels that intensify coastal flooding and storm surge. Certain groups of people are more vulnerable to the range of climate change-related health impacts, including the elderly, children, the poor, and the sick. Others are vulnerable because of where they live, including those in floodplains, coastal zones, and some urban areas. In fact, U.S. population growth has been greatest in coastal zones and in the arid Southwest, areas that already have been affected by increased risks from climate change. Just as some choices can make us more vulnerable, other choices can make us more resilient. Maintaining a robust public health infrastructure will be critical to managing the potential health impacts of climate change (Ch. 2,7,9,11,12,13,16,18,20,25).

Climate change affects the entire living world, including people, through changes in ecosystems and biodiversity. Ecosystems provide a rich array of benefits to humanity, including fisheries, drinking water, fertile soils for growing crops, buffering from climate impacts, and aesthetic and cultural values. These benefits are not always easy to quantify, but they translate into jobs, economic growth, health, and human well-being. Climate change-driven perturbations to ecosystems that have direct human impacts include reduced water supply and quality, the loss of iconic species and landscapes, distorted rhythms of nature, and the potential for extreme events to eliminate the capacity of ecosystems to provide benefits (Ch. 3, 6, 8, 12, 14, 23, 24).

Climate change and other human modifications of ecosystems and landscapes often increase their vulnerability to damage from extreme events while at the same time reducing their natural capacity to modulate the impacts of such events. Salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure, including roads and buildings, against storm surges; their losses from coastal development, erosion, and sea level rise increase the risk of catastrophic damage during or after extreme weather events. Floodplain wetlands, although greatly reduced from their historical extent, absorb floodwaters and reduce the effects of high flows on river-margin lands. Extreme weather events that produce sudden increases in water flow, often carrying debris and pollutants, can decrease the natural capacity of ecosystems to process pollutants (Ch. 3, 7, 8, 25).

As climate change and its impacts are becoming more prevalent, Americans face choices. As a result of past emissions of heat-trapping gases, some amount of additional climate change and related impacts is now unavoidable. This is due to the long-lived nature of many of these gases, the amount of heat absorbed and retained by the oceans, and other responses within the climate system. However, beyond the next few decades, the amount of climate change will still largely be determined by choices society makes about emissions. Lower emissions mean less future warming and less severe impacts; higher emissions would mean more warming and more severe impacts. The choices about emissions pathway fall into a category of response options usually referred to as "mitigation" – ways to reduce the amount and speed of future climate change by reducing emissions of heat-trapping gases (Ch. 2, 26, 27).

The other major category of response options is known as "adaptation" and refers to changes made to better respond to new conditions, thereby reducing harm or taking advantage of opportunity. Mitigation and adaptation are linked, in that effective mitigation reduces the need for adaptation. Both are essential parts of a comprehensive response strategy. The threat of irreversible impacts makes the timing of mitigation efforts particularly critical. This report includes chapters on Mitigation, Adaptation, and Decision Support that offer an overview of the kinds of options and activities being planned or implemented around the country as governments at local, state, federal, and tribal levels, businesses, other organizations, and individuals begin to respond to climate change (Ch. 26, 27, 28).

Large reductions in global emissions, similar to the lower emissions scenario (B1) analyzed in this assessment, would be necessary to avoid some of the worst impacts and risks of climate change. The targets called for in international agreements would require even larger reductions than those outlined in scenario B1 (Figure 1). Meanwhile, global emissions are still rising, and are on track to be even higher than the high emissions scenario (A2) analyzed in this report. The current U.S. contribution to global emissions is about 20%. Voluntary efforts, the recent shift from coal to natural gas for electricity generation, and governmental actions in city, state, regional, and federal programs under way and have contributed to reducing U.S. emissions in the last few years. Some of these actions are motivated by climate concerns, sometimes with non-climate co-benefits, while others are motivated primarily by non-climate objectives. These U.S. actions and others that might be undertaken in the future are described in the Mitigation chapter of this report; at present they are not sufficient to reduce total U.S. emissions to a level that would be consistent with scenario B1 or the targets in international agreements (Ch. 2, 4, 27).

With regard to adaptation, the pace and magnitude of observed and projected changes emphasize the need for being prepared for a wide variety and intensity of climate impacts. Because of the influence of human activities, the past climate is no longer a sufficient indicator of future conditions. Planning and managing based on the climate of the last century means that tolerances of some infrastructure and species will be exceeded. For example, building codes and landscaping ordinances will likely need to be updated not only for energy efficiency, but also to conserve water supplies, protect against insects that spread disease, reduce susceptibility to heat stress, and improve protection against extreme events. The knowledge that climate change is real and accelerating points to the need to develop and refine approaches that enable decision-making and increase flexibility, robustness, and resilience in the face of ongoing and future impacts. Being prepared for such events paves the way for economic opportunities (Ch. 2, 3, 5, 9, 11, 13, 26, 27, 28).

Adaptation considerations include local, state, regional, national, and international jurisdictional issues. For example, in managing water supplies to adapt to a changing climate, the implications of international treaties should be considered in the context of managing the Great Lakes, the Columbia River, and the Colorado River to deal with increased drought risk. Both “bottom up” community planning and “top down” national strategies may help regions deal with impacts such as increases in electrical brownouts, heat stress, floods, and wildfires. Such a mix of approaches will require cross-boundary coordination at multiple levels as operational agencies integrate adaptation planning into their programs (Ch. 3, 7, 9, 10, 18, 20, 21, 26, 28).

Proactively preparing for climate change can reduce impacts, while also facilitating a more rapid and efficient response to changes as they happen. The Adaptation chapter in this report highlights efforts at the federal, regional, state, tribal, and local levels, as well as initiatives in the corporate and non-governmental sectors to build adaptive capacity and resilience towards climate change (Ch. 28).

This report identifies a number of areas for which improved scientific information or understanding would enhance the capacity to estimate future climate change impacts. For example, knowledge of the mechanisms controlling the rate of ice loss in Greenland and Antarctica is limited, making it difficult for scientists to narrow the range of future sea level rise. Research on ecological responses to climate change is limited, as is understanding of social responses and how ecological and social responses will interact (Ch. 29).

There is also a section on creating a sustained climate assessment process to more efficiently collect and synthesize the rapidly evolving science and to help supply timely and relevant information to decision-makers. Results from all of these efforts will continue to build our understanding of the interactions of human and natural systems in the context of a changing climate (Ch. 30).

Report Findings

1. Global climate is changing, and this is apparent across the U.S. in a wide range of observations. The climate change of the past 50 years is due primarily to human activities, predominantly the burning of fossil fuels.
U.S. average temperature has increased by about 1.5°F since 1895, with more than 80% of this increase occurring since 1980. The most recent decade was the nation's warmest on record. Because human-induced warming is superimposed on a naturally varying climate, rising temperatures are not evenly distributed across the country or over time (Ch. 2).

2. Some extreme weather and climate events have increased in recent decades, and there is new and stronger evidence that many of these increases are related to human activities.
Changes in extreme events are the primary way in which most people experience climate change. Human-induced climate change has already increased the frequency and intensity of some extremes. Over the last 50 years, much of the U.S. has seen an increase in prolonged stretches of excessively high temperatures, more heavy downpours, and in some regions more severe droughts (Ch. 2, 16, 17, 18, 19, 20, 23).

3. Human-induced climate change is projected to continue and accelerate significantly if emissions of heat-trapping gases continue to increase.
Heat-trapping gases already in the atmosphere have committed us to a hotter future with more climate-related impacts over the next few decades. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, now and in the future (Ch. 2, 27).

4. Impacts related to climate change are already evident in many sectors and are expected to become increasingly challenging across the nation throughout this century and beyond.
Climate change is already affecting human health, infrastructure, water resources, agriculture, energy, the natural environment, and other factors – locally, nationally, and internationally. Climate change interacts with other environmental and societal factors in a variety of ways that either moderate or exacerbate the ultimate impacts. The types and magnitudes of these effects vary across the nation and through time. Several populations – including children, the elderly, the sick, the poor, tribes and other indigenous people – are especially vulnerable to one or more aspects of climate change. There is mounting evidence that the costs to the nation are already high and will increase very substantially in the future, unless global emissions of heat-trapping gases are strongly reduced (Ch. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25).

5. Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, diseases transmitted by insects, food, and water, and threats to mental health.
Climate change is increasing the risks of heat stress, respiratory stress from poor air quality, and the spread of waterborne diseases. Food security is emerging as an issue of concern, both within the U.S. and across the globe, and is affected by climate change. Large-scale changes in the environment due to climate change and extreme weather events are also increasing the risk of the emergence or reemergence of unfamiliar health threats (Ch. 2, 6 , 9, 11, 12, 16, 19,

20, 22, 23).

6. Infrastructure across the U.S. is being adversely affected by phenomena associated with climate change, including sea level rise, storm surge, heavy downpours, and extreme heat.

Sea level rise and storm surges, in combination with the pattern of heavy development in coastal areas, are already resulting in damage to infrastructure such as roads, buildings, ports, and energy facilities. Infrastructure associated with military installations is also at risk from climate change impacts. Floods along the nation's rivers, inside cities, and on lakes following heavy downpours, prolonged rains, and rapid melting of snowpack are damaging infrastructure in towns and cities, farmlands, and a variety of other places across the nation. Extreme heat is damaging transportation infrastructure such as roads, rail lines, and airport runways. Rapid warming in Alaska has resulted in infrastructure impacts due to thawing of permafrost and the loss of coastal sea ice that once protected shorelines from storms and wave-driven coastal erosion (Ch. 2, 3, 5, 6, 11, 16, 17, 18, 19, 20, 21, 22, 23, 25).

7. Reliability of water supplies is being reduced by climate change in a variety of ways that affect ecosystems and livelihoods in many regions, particularly the Southwest, the Great Plains, the Southeast, and the islands of the Caribbean and the Pacific, including the state of Hawai`i.

Surface and groundwater supplies in many regions are already stressed by increasing demand for water as well as declining runoff and groundwater recharge. In many regions, climate change increases the likelihood of water shortages and competition for water among agricultural, municipal, and environmental uses. The western U.S. relies heavily on mountain snowpack for water storage, and spring snowpack is declining in most of the West. There is an increasing risk of seasonal water shortages in many parts of the U.S., even where total precipitation is projected to increase. Water quality challenges are also increasing, particularly sediment and contaminant concentrations after heavy downpours (Ch. 2, 3, 12, 16, 17, 18, 19, 20, 21, 23).

8. Adverse impacts to crops and livestock over the next 100 years are expected. Over the next 25 years or so, the agriculture sector is projected to be relatively resilient, even though there will be increasing disruptions from extreme heat, drought, and heavy downpours. U.S. food security and farm incomes will also depend on how agricultural systems adapt to climate changes in other regions of the world.

Near-term resilience of U.S. agriculture is enhanced by adaptive actions, including expansion of irrigated acreage in response to drought, regional shifts in crops and cropped acreage, continued technological advancements, and other adjustments. By mid-century, however, when temperature increases and precipitation extremes are further intensified, yields of major U.S. crops are expected to decline, threatening both U.S. and international food security. The U.S. food system also depends on imports, so food security and commodity pricing will be affected by agricultural adaptation to climate changes and other conditions around the world (Ch. 2, 6, 12, 13, 14, 18, 19).

9. Natural ecosystems are being directly affected by climate change, including changes in biodiversity and location of species. As a result, the capacity of ecosystems to moderate the consequences of disturbances such as droughts, floods, and severe storms is being diminished.

In addition to climate changes that directly affect habitats, events such as droughts, floods, wildfires, and pest outbreaks associated with climate change are already disrupting ecosystem structures and functions in a variety of direct and indirect ways. These changes limit the capacity of ecosystems such as forests, barrier beaches, and coastal- and freshwater-wetlands to adapt and continue to play important roles in reducing the impacts of these extreme events on infrastructure, human communities, and other valued resources (Ch. 2, 3, 6, 7, 8, 10, 11, 14, 15, 19, 25).

10. Life in the oceans is changing as ocean waters become warmer and more acidic.

Warming ocean waters and ocean acidification across the globe and within U.S. marine territories are broadly affecting marine life. Warmer and more acidic waters are changing the distribution of fish and other mobile sea life, and stressing those, such as corals, that cannot move. Warmer and more acidic ocean waters combine with other stresses, such as overfishing and coastal and marine pollution, to negatively affect marine-based food production and fishing communities (Ch. 2, 23, 24, 25).

11. Planning for adaptation (to address and prepare for impacts) and mitigation (to reduce emissions) is increasing, but progress with implementation is limited.

In recent years, climate adaptation and mitigation activities have begun to emerge in many sectors and at all levels of government; however barriers to implementation of these activities are significant. The level of current efforts is insufficient to avoid increasingly serious impacts of climate change that have large social, environmental, and economic consequences. Well-planned and implemented actions to limit emissions and increase resilience to impacts that are unavoidable can improve public health, economic development opportunities, natural system protection, and overall quality of life (Ch. 6, 7, 8, 9, 10, 13, 15, 26, 27, 28).

Table 1.1: Regional Observations of Climate Change

Regional Observations of Climate Change	
Northeast	Heat waves, coastal flooding due to sea level rise and storm surge, and river flooding due to more extreme precipitation events are affecting communities in the region.
Southeast	Decreased water availability, exacerbated by population growth and land-use change, is causing increased competition for water; risks associated with extreme events like hurricanes are increasing.
Midwest	Longer growing seasons and rising carbon dioxide levels are increasing yields of some crops, although these benefits have already been offset in some instances by occurrence of extreme events such as heat waves, droughts, and floods.
Great Plains	Rising temperatures are leading to increased demand for water and energy and impacts on agricultural practices.
Southwest	Drought and increased warming have fostered wildfires and increased competition for scarce water resources for people and ecosystems.
Northwest	Changes in the timing of streamflow related to earlier snowmelt have already been observed and are reducing the supply of water in summer, causing far-reaching ecological and socioeconomic consequences.
Alaska	Summer sea ice is receding rapidly, glaciers are shrinking, and permafrost is thawing, causing damage to infrastructure and major changes to ecosystems; impacts to Alaska native communities are increasing.
Hawaii	Increasingly constrained freshwater supplies, coupled with increased temperatures, are stressing both people and ecosystems, and decreasing food and water security.
Coasts	Coastal lifelines, such as water supply infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate-related changes.
Oceans	The oceans are currently absorbing about a quarter of human-caused carbon dioxide emissions to the atmosphere and over 90% of the heat associated with global warming, leading to ocean acidification and the alteration of marine ecosystems.

Crosscutting Themes and Issues

There are several themes that run throughout the assessment. These include: the "multiple stresses context" in which climate change impacts must be interpreted; the effects of socioeconomic and cultural decisions on vulnerabilities to climate change; and the importance of considering climate-change impacts on the U.S. in an international context.

1. Climate change should be considered in the context of multiple factors

Climate change and its impacts cannot be adequately assessed in isolation. Rather, they are part of a broader context including many other factors such as: land-use change, local economies, air and water pollution, and rates of consumption of resources. This perspective has implications for assessments of climate change impacts and the design of research questions at the national, regional, and local scales. This assessment begins to explore the consequences of interacting factors by focusing on sets of crosscutting issues in a series of six chapters: Water, Energy, and Land Use; Biogeochemical Cycles; Impacts of Climate Change on Tribal Lands and Resources; Urban Infrastructure and Vulnerability; Land Use and Land Cover Change; and Impacts on Rural Communities. This Assessment also includes discussions of cascading impacts in several chapters (particularly in the Urban Infrastructure and Vulnerability Chapter and the Water, Energy, and Land Use Chapter), and emphasizes that many of the impacts identified in the Assessment will occur in parallel, not in isolation from one another. As illustrated by recent events, this greatly stresses the capacity to respond to a series of climate-related crises that occur simultaneously or soon after one another.

2. Societal choices affect vulnerability to climate change impacts.

Because environmental, cultural and socioeconomic systems are tightly coupled, climate change impacts can either be amplified or reduced by cultural and/or socioeconomic decisions. In the context of the "risk-based framing" for their chapters, the authors of this report were asked to focus on attributes of regions and sectors most likely to experience significant impacts. In many chapters, it is clear that societal decisions have the greatest impact on valued resources. For example, rapid population growth and development in areas that are particularly susceptible to climate change impacts can amplify those impacts. Recognition of these couplings, together with recognition of the multiple-stresses perspective, helps identify the information needs of decision-makers as they manage risk.

3. Importance of the international context

Climate change is a global phenomenon; the causes and the impacts involve energy-use and risk-management decisions across the globe. Impacts, vulnerabilities, and opportunities in the U.S. are related in complex and interactive ways with changes outside the U.S., and vice versa. In order for U.S. concerns related to climate change to be addressed comprehensively, the international context must be considered. U.S. security, foreign assistance, and economic interests are affected by climate changes experienced in other parts of the world. Although there is significantly more work to be done in this area, this report does identify some initial implications of global and international trends that can be more fully investigated in future assessments.

4. Thresholds, Tipping Points, and Surprises

A significant issue in studying and preparing for global climate change is the fact that changes in human, social, and physical systems do not always occur gradually. Same changes may occur in a relatively predictable way, while others involve unexpected break-points or thresholds beyond which there are irreversible changes or changes of higher magnitudes than expected based on previous experience. These "tipping points" are very hard to predict, as there are many uncertainties associated with understanding future conditions. These uncertainties come from a number of sources, including insufficient data associated with low probability/high consequence events, models that are not yet able to represent the interactions of multiple stresses, incomplete understanding of physical climate mechanisms related to tipping points, and a multitude of issues associated with human behavior, risk management, and decision-making.

5. Weather and Climate Extremes

Understanding how climate is changing requires consideration of changes in the average climate as well as changes in "extremes" – weather and climate events like hot spells, heavy rains, periods of drought and flooding, and severe storms. The climate change impacts expected to have the greatest consequences are those involving extremes: changes in the frequency, intensity, timing, duration, and spatial extent of such extremes, as well as through the occurrence of unprecedented extremes.

Terms like "weather-extremes," "climate extremes," "heat waves," and "heavy downpours" need to be defined when used in a scientific context. Researchers use different definitions depending on which characteristics of extremes they are choosing to explore at any one time, in the context of the particular issue they are studying. Nevertheless, most of the scientific literature on extremes uses definitions that fall roughly into two categories (IPCC 2012): those related to the probability of occurrence of a certain type of event, and those related to exceeding a particular threshold.

For example, common measures of extremes include the number, percentage, or fraction of days in a month, season, or year with maximum (or minimum) temperature above the 90th, 95th, or 99th percentile compared to a reference time period (for example, 1961-1990) – or alternatively, how often a threshold temperature (for example, 32°F or 90°F) is exceeded during a given decade. Alternative definitions refer to how often, on average, an event of a specific magnitude occurs (sometimes called the "return period") – for example, how frequently we might expect to see daily rainfall exceeding two inches in a given region.

In addition, extremes occur over different time periods, ranging from events lasting a few days to a few weeks, like a heat wave or cold snap, to those that happen over longer timescales, such as a period of drought or an unusually hot summer.

Changes in extremes are often more difficult to study than changes in the average climate because of the smaller data sample for particularly rare events. This is less of an issue for so-called "moderate extremes," such as those occurring as often as 5% to 10% of the time. For more "extreme extremes," statistical methods are often used to overcome these sampling issues.

For any given aspect of climate, such as temperature or precipitation, it is important to look at a variety of measures to get an overall picture of the changes in extremes. For the several types of extremes discussed in Chapter 2: Our Changing Climate under Key Messages 6, 7, and 8, for example, the cited studies address different, complementary aspects of each of these phenomena. In the impact studies cited in other chapters, the word "extreme" is often defined differently within different sectors, such as water or health. However, collectively, these studies paint a consistent picture of changes in average climate as well as changes across a range of weather and climate extremes in the United States.

About This Report

The development of this draft National Climate Assessment (NCA) report was overseen by the 60-member National Climate Assessment and Development Advisory Committee (NCADAC), a Federal Advisory Committee (FAC) appointed by the Secretary of Commerce at the request of the National Science and Technology Council (NSTC). The NSTC is required, under the 1990 Global Change Research Act (GCRA, Title 15 USC Sec 2921 2012), to provide such reports periodically to the President and the Congress. The report, which assesses current scientific findings about the observed and projected impacts of climate change on the United States, relies heavily on the findings of the U.S. Global Change Research Program (USGCRP) (USGCRP 2012). USGCRP activities include observations, monitoring, modeling, process research, and data management focused on discerning global change impacts and informing response options such as adaptation and mitigation. After government review, this report is expected to become the third National Climate Assessment (Karl et al. 2009; USGCRP 2000).

As required by Section 106 of the GCRA, the NCA integrates, evaluates, and synthesizes the science of climate and global change and the observed and projected impacts of climate change on the U.S. The assessment integrates the findings of USGCRP with climate-change research and scientific observations from around the world. Major topics in the assessment include evaluating current understanding of climate change science as well as related impacts on various societal and environmental sectors and regions across the nation. The goal of this assessment report is to establish a scientific and credible foundation of information that is useful for a variety of science and policy applications related to managing risk and maximizing opportunities in a changing climate. The report also documents some societal responses to climate changes, and gives public and private decision-makers a better understanding of how climate change is affecting us now and what is in store for the future.

Authorship and Review and Approval Process

A team of more than 240 experts operating under the authority of the NCADAC wrote this document. The NCADAC was assisted by the staff of the USGCRP National Coordination Office, a Technical Support Unit located at the NOAA National Climatic Data Center, and communication specialists in development of this draft report. The report will be extensively reviewed and revised based on comments from the National Research Council of the National Academies of Science and the public. It will then be submitted for review and approval by the National Oceanic and Atmospheric Administration, other agencies of the Subcommittee on Global Change Research, the Committee on the Environment and Natural Resources of the NSTC, and the NSTC itself. Upon approval, the report will be transmitted to Congress and the President. The entire process is designed to ensure that the report meets all federal requirements associated with the Information Quality Act, including those pertaining to public comment and transparency (OMB 2012).

Stakeholder Engagement

This third National Climate Assessment effort has included extensive involvement of stakeholders in providing inputs to the structure and substance of the report. Teams of regional and sectoral experts, decision-makers, and stakeholders were formed to provide technical input and data to the Assessment process. Stakeholder and expert groups participated in more than 70 workshops and listening sessions. Participants included public and private decision-makers, resource and environmental managers, researchers, non-governmental organizations, and the general public (USCGCRP 2012). Stakeholders from various regions and sectors identified climate-change issues and information they asked to be considered in the assessment. In addition, a number of stakeholder groups submitted data and written reports related to their knowledge about specific climate change issues in response to a request for such input through the Federal Register. A communications and engagement workgroup of the FAC provided oversight and advice regarding the events and engagement processes that led to this report.

Sources of Information

The report draws from a large body of scientific peer-reviewed research published or in press by July 31, 2012. This new work was carefully reviewed by the author teams to ensure a reliable assessment of the state of scientific understanding. Another important source of information for this report was a set of technical input reports produced by federal agencies and other interested parties in response to a request for information by the Assessment's federal advisory committee (USGCRP 2012). In addition, other peer-reviewed scientific assessments were used, including those of the Intergovernmental Panel on Climate Change, the U.S. National Assessment's 2009 report, *Global Climate Change Impacts in the United States* (Karl et al. 2009), the National Academy of Science's *America's Climate Choices* reports (NRC 2011), and a variety of regional climate impact assessments. These assessments were augmented with government statistics as necessary (such as population census and energy usage) as well as publicly available observations. The final version of this report will be deployed electronically as an "e-book," allowing for linkages across and within topics and chapters as well as transparent, clickable access to the data and references behind each of the conclusions.

Responding to Climate Change

While the primary focus of this report is on the impacts of climate change in the U.S., it also documents some of the actions society is already taking or can take to respond to the climate challenge. Responses to climate change fall into two broad categories. The first involves "mitigation" measures to reduce climate change by reducing emissions of heat-trapping gases and particles, or increasing removal of carbon dioxide from the atmosphere. The second involves "adaptation" measures to improve society's ability to cope with or avoid harmful impacts and take advantage of beneficial ones, now and in the future. At this point, both of these response activities are necessary to limit the magnitude and impact of global climate change on the United States. More effective mitigation measures can reduce the amount of climate change, and therefore the need for adaptation in the future.

This report underscores the effect of mitigation by comparing impacts resulting from higher versus lower emissions scenarios. This shows that choices made about emissions in the next few decades will have far-reaching consequences for climate change impacts in the middle to latter part of this century. Over the long term, lower emissions will lessen both the magnitude of climate change impacts and the rate at which they appear.

While the report underscores the importance of mitigation as an essential part of the nation's climate change strategy, it does not evaluate mitigation technologies or undertake an analysis of the effectiveness of various approaches. These issues are the subject of ongoing studies by the

U.S. Government's Climate Change Technology Program and several federal agencies including the Department of Energy, Environmental Protection Agency, Department of Transportation, and Department of Agriculture. The range of mitigation responses being studied by these agencies includes, but is not limited to, more efficient production and use of energy, increased use of non-carbon-emitting energy sources, and carbon capture and storage.

Adaptation actions are complementary to mitigation options. They are focused on moderating harmful impacts of current and future climate variability and change, and taking advantage of possible beneficial opportunities arising from climate change. While this report does assess the current state of adaptation actions and planning across the country, the implementation of adaptive actions is still nascent, and a comprehensive assessment of actions taken, and of their effectiveness, is not yet possible. This report documents actions currently being pursued to address impacts such as increased urban heat extremes and air pollution, and describes the challenges decision makers face in planning for and implementing adaptation responses.

Risk-Based Framing

Authors of this assessment were asked to approach it from the perspective of a decision-maker trying to limit risk to valued systems, resources, and communities (and to consider opportunities as well). For each chapter, they were asked to frame a number of key questions or issues that address the most important information needs of stakeholders, and consider the decisions stakeholders are facing. The criteria provided for identifying key vulnerabilities in their sector or region included: magnitude, timing, persistence/reversibility, distributional aspects, likelihood, and importance of impacts (based on the perceptions of relevant parties) as well as the potential for adaptation. For the purposes of this assessment, risk was defined as the product of likelihood and consequence, and authors were encouraged to think about these topics from both a quantitative and qualitative perspective, and to consider the influence of multiple stresses if possible.

Assessing Confidence

The level of confidence the chapter authors have in the key findings they report is given in "traceable accounts" that accompany each chapter. A traceable account is intended to: 1) document the process the authors used to come to the conclusions in their key messages; 2) provide additional information to reviewers about the quality of the information used; and 3) allow traceability to data and resources. The authors have assessed a wide range of information in the scientific literature and previous technical reports. In assessing confidence, they have considered the strength and consistency of the observed evidence, the skill, range, and consistency of model projections, and insights about processes and climate from peer-reviewed sources.

Assessing Likelihood

When it is considered scientifically justified to report the likelihood of particular impacts within the range of possible outcomes, this report takes a plain-language approach to expressing the expert judgment of the author team based on the best available evidence. For example, an outcome termed "likely" has at least a two-thirds chance of occurring; an outcome termed "very likely," at least a 90% chance. Key sources of information used to develop these characterizations of uncertainty are referenced.

Addressing Incomplete Scientific Understanding

Within each traceable account, the authors identify areas where a lack of information and/or scientific uncertainty limits their ability to estimate future climate change and its impacts. The section on "An Agenda for Climate Impacts Science" at the end of this report highlights some of the areas suggested for additional research.

Scenarios

Scenarios are ways to help understand what future conditions might be, with each scenario an example of what might happen under particular assumptions. Scenarios are not predictions or forecasts. Instead, scenarios provide a starting point for examining questions about an uncertain future and help us to visualize alternative futures in concrete and human terms. The military and businesses frequently use these powerful tools for future planning in high-stakes situations. We use scenarios to help identify future vulnerabilities as well as to support decision-makers who are focused on limiting risk and maximizing opportunities. Three types of scenarios are used in this assessment – emissions scenarios (including population and land use components), climate scenarios, and sea level rise scenarios.

Emissions Scenarios

Emissions scenarios quantitatively illustrate potential additions to the atmosphere of substances that alter natural climate patterns. Emissions result from essential human activities, including energy production and use, agriculture, and other activities that change land use. These scenarios are developed using a wide range of assumptions about population growth, economic development, the evolution of technology, and decisions about environmental protection, among other factors. A wide range of assumptions is used because future trends are uncertain and depend on unpredictable human choices. These assumptions about the future include a wide array of considerations – not only emissions, but also the extent to which changes in climate will have impacts on society and natural resources, and capacity for adaptation.

Perspectives on "plausible" emissions scenarios evolve over time. The Intergovernmental Panel on Climate Change (IPCC) has been a leader in developing scenarios and has released three different sets since 1990. In 2000, the IPCC released a Special Report on Emission Scenarios (Nakicenovic et al. 2000) that provided its most recent set of scenarios (known as SRES) that described a wide range of socioeconomic futures and resulting emissions. In the higher end of the range, the SRES A2 scenario represents a divided world with high population growth, low economic growth, slower technology improvements and diffusion, and other factors that contribute to high emissions and lower adaptive capacity (for example, low per capita wealth). At the lower end of the range, the B1 scenario represents a world with lower population growth, higher economic development, a shift to low-emitting efficient energy technologies that are diffused rapidly around the world through free trade, and other conditions that reduce the rate and magnitude of changes in climate averages and extremes as well as increased capacity for adaptation. Recently, a new set of scenarios (Representative Concentration Pathways – RCPs) has been prepared and released by scientists who study emissions, climate, and potential impacts (Moss et al. 2010). This new set incorporates recent observations and research and includes a wider range of future conditions and emissions. Because climate model results are just now being prepared using the new scenarios, and there are few impacts studies that employ them, when scenarios are needed, the report uses the SRES B1 and A2 to span a range of potential futures.

Scientists cannot predict which of these scenarios is most likely because the future emissions pathway is a function of human choices. A wide range of societal decisions and policy choices will ultimately influence how the world's emissions evolve, and ultimately, the composition of the atmosphere and the state of the climate system.

Climate Scenarios

Global models that simulate the Earth's climate system are used, among other things, to evaluate the effects of human activities on climate. Since the second U.S. National Climate Assessment report in 2009, a new set of model simulations has been introduced that include more Earth system physics and chemistry and have higher resolution.

These models use emissions scenarios to project expected climate change given different assumptions about how human activities and/or associated emissions levels might change.

The range of potential increases in global average temperature in the newest climate model simulations is wider because a wider range of options for future human behavior is considered. For example, one of the new RCP scenarios assumes rapid emission reductions that would limit the global temperature increase to about 3.7°F, a much lower level than in previous scenarios. However, it is noteworthy that the emissions trajectory in RCP 8.5 is similar to SRES A2 and RCP 4.5 is roughly comparable to SRES B1 (see figure comparing SRES and RCP scenarios below).

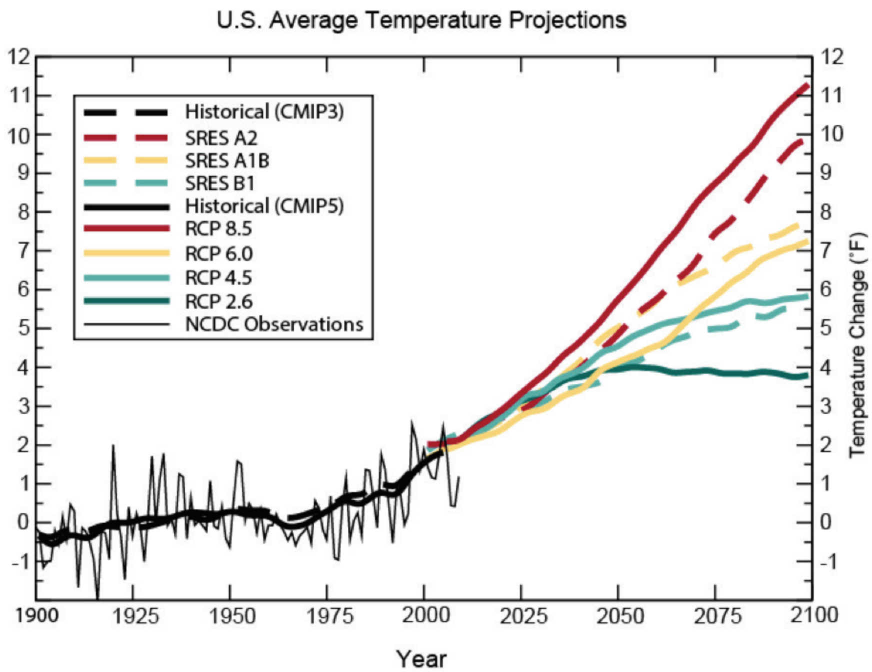

Figure 1.1: U.S. Average Temperature Projections

Caption: Projected average annual temperature changes (°F) over the contiguous U.S. for multiple future emissions scenarios, relative to the 1901-1960 average temperature. The dashed lines are results from the SRES scenarios and the previous simulations. The solid lines are results from RCPs and the most recent simulations. (Figure source: Michael Wehner, LBNL. Data from CMIP3, CMIP5, and NOAA.)

Box: Emissions Scenarios
In this report, the two SRES emissions scenarios recommended for use in impact studies are a higher emissions scenario (the A2 scenario from SRES) and a lower emissions scenario (the B1 scenario from SRES). These two scenarios do not encompass the full range of possible futures: emissions can change less than those scenarios imply, or they can change even more. Recent carbon dioxide emissions are, in fact, above the A2 scenario. Whether this will continue is unknown.

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Sea Level Rise Scenarios
After at least two thousand years of little change, sea level rose by roughly 8 inches over the last century, and satellite data provide evidence that the rate of rise over the past 20 years has roughly doubled. In the U.S., millions of people and many of the nation's assets related to military readiness, energy, transportation, commerce, and ecosystems are located in areas at risk of coastal flooding because of sea level rise and storm surge.

Sea level is rising because ocean water expands as it heats up and because water is added to the oceans from melting glaciers and ice sheets. Sea level is projected to rise an additional 1 to 4 feet in this century. Scientists are unable to narrow this range at present because the processes affecting the loss of ice mass from the large ice sheets are dynamic and still the subject of intense study. Some impact assessments in this report use a set of sea level rise scenarios within this range, while others consider sea level rise as high as 6.6 feet.

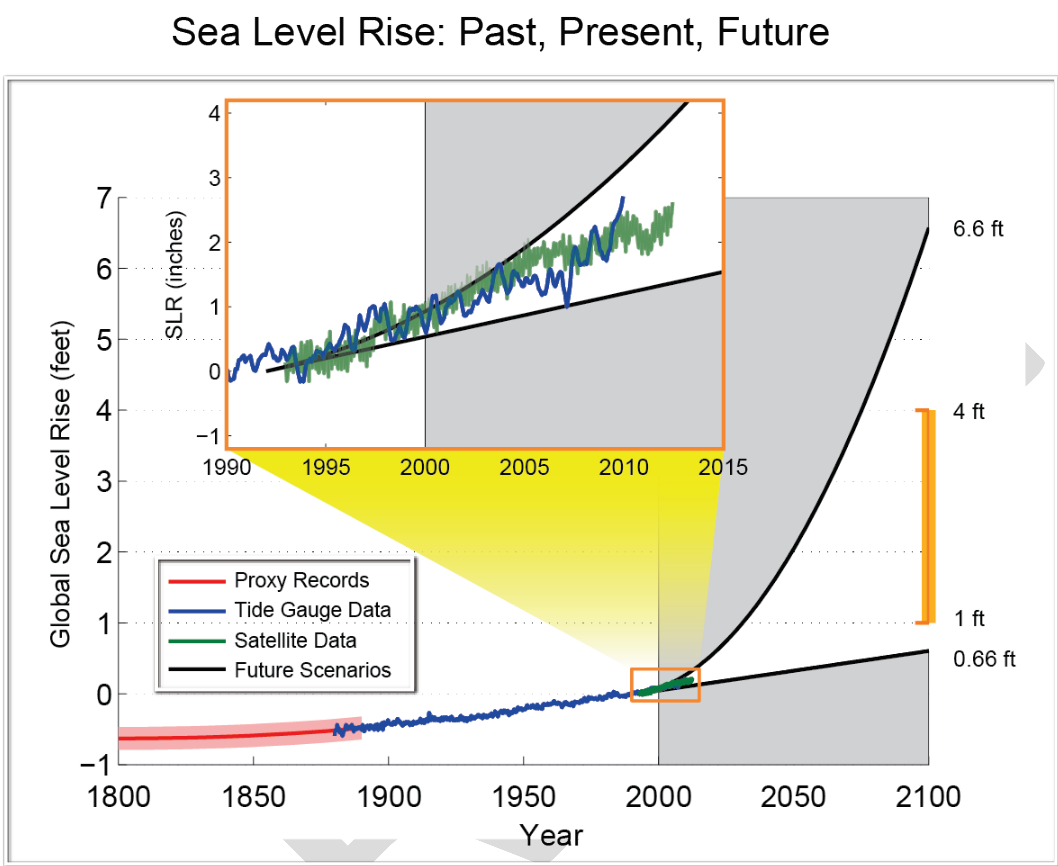

Figure 1.2: Sea Level Rise: Past, Present, and Future

Caption: Historical, observed, and possible future amounts of global sea level rise from 1800 to 2100. Historical estimates (Kemp et al. 2012) (based on sediment records and other proxies) are shown in red (pink band shows uncertainty range), tide gauge measurements in blue (Church and White 2011), and satellite observations are shown in green (Nerem et al. 2010). The future scenarios range from 0.66 feet to 6.6 feet in 2100 (Parris et al. 2012). Higher or lower amounts of sea level rise are considered implausible by 2100, as represented by the gray shading. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100, which falls within the larger risk-based scenario range. The large projected range of scenarios reflects uncertainty about how ice sheets will respond to the warming ocean and atmosphere, and to changing winds and currents. Figure source: Josh Willis, NASA Jet Propulsion Laboratory, based on cited data sources.

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2. Our Changing Climate

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Key Messages

1. **Global climate is changing now and this change is apparent across a wide range of observations. Much of the climate change of the past 50 years is primarily due to human activities.**
2. **Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the climate is to those emissions.**
3. **U.S. average temperature has increased by about 1.5°F since record keeping began in 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's warmest on record. U.S. temperatures are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, smooth across the country or over time.**
4. **The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases**

occurring in the western U.S., affecting ecosystems and agriculture. Continued lengthening of the growing season across the U.S. is projected.

5. **Precipitation averaged over the entire U.S. has increased during the period since 1900, but regionally some areas have had increases greater than the national average, and some areas have had decreases. The largest increases have been in the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century.**

6. **Heavy downpours are increasing in most regions of the U.S., especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas.**

7. **Certain types of extreme weather events have become more frequent and intense, including heat waves, floods, and droughts in some regions. The increased intensity of heat waves has been most prevalent in the western parts of the country, while the intensity of flooding events has been more prevalent over the eastern parts. Droughts in the Southwest and heat waves everywhere are projected to become more intense in the future.**

8. **There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm; ocean cycles will also affect the amount of warming at any given time. With regard to other types of storms that affect the U.S., winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the U.S. Other trends in severe storms, including the numbers of hurricanes and the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds are uncertain and are being studied intensively.**

9. **Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.**

10. **Rising temperatures are reducing ice volume and extent on land, lakes, and sea. This loss of ice is expected to continue.**

11. **The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about potential impacts on marine ecosystems.**

Our Changing Climate

This chapter summarizes how climate is changing, why it is changing, and what is projected for the future. While the focus is on changes in the United States, the need to provide context requires a broader geographical perspective in some parts of the discussion. Additional geographic detail is presented in the regional chapters of this report. Further details on the topics of this chapter are provided in the Appendix.

Since the previous national climate assessment was published in 2009, the climate has continued to change, with resulting effects on the U.S. The trends described in the 2009 report have continued, and our understanding of the data and ability to model the many facets of the climate system have increased substantially. Several noteworthy advances are mentioned below.

What's New?

- Continued warming and an increased understanding of the U.S. temperature record, as well as multiple other sources of evidence, have strengthened our confidence in the conclusions that the warming trend is clear and primarily the result of human activities.
- Heavy precipitation and extreme heat events are increasing in a manner consistent with model projections; the risks of such extreme events will rise in the future.
- The sharp decline in summer Arctic sea ice has continued, is unprecedented, and is consistent with human-induced climate change. 2012 has set a new record for minimum area of Arctic ice.
- A longer and better-quality history of sea level rise has increased confidence that recent trends are unusual and human-induced. Limited knowledge of ice sheet dynamics leads to a broad range of potential increases over this century.
- New approaches to building scenarios of the future have allowed for investigations of the implications of deliberate reductions in heat-trapping gas emissions.

Eleven key messages are presented below, together with supporting evidence. The discussion of each key message begins with a summary of recent variations or trends, followed by information on the corresponding changes projected for the future.

Observed Climate Change

Global climate is changing now and this change is apparent across a wide range of observations. Much of the climate change of the past 50 years is due primarily to human activities.

Many aspects of the global climate are changing rapidly, and the primary drivers of that change are human in origin. Evidence for climate change abounds, from the top of the atmosphere to the depths of the oceans (Kennedy et al. 2010). This evidence has been painstakingly compiled by scientists and engineers from around the world using satellites, weather balloons, thermometers at surface stations, and many other types of observing systems that monitor the Earth's climate system. The sum total of this evidence tells an unambiguous story: the planet is warming. Temperatures at the surface, in the troposphere (the active weather layer extending up to about 8 to 12 miles above the ground), and in the oceans have all increased over recent decades. Snow and ice cover have decreased in most areas. Atmospheric water vapor due to increased evaporation from the warmer surface has been increasing in the lower atmosphere, as have sea levels. Changes in other climate-relevant indicators such as growing season length have been observed in many areas. Worldwide, the observed changes in average conditions have been accompanied by trends in extremes of heat, cold, drought, and heavy precipitation events (Alexander et al. 2006).

Climate model simulations reinforce scientific understanding that observed variations in global average surface temperature over the past century can only be explained through a combination of human and natural factors. However, natural drivers of climate cannot explain the recent observed warming; over the last five decades, natural factors (solar forcing and volcanoes) alone would actually have led to a slight cooling (Gillett et al. 2012). Natural variability, including the effects of El Niño and La Niña events and various ocean cycles, also affects climate, but the changes observed over the past 50 years are far larger than natural variability can account for. The majority of the warming can only be explained by the effects of human influences (Gillett et al. 2012; Stott et al. 2010), especially the emissions from burning of fossil fuels such as coal, oil, and natural gas. This robust scientific attribution of observed changes to human influence extends to many other climate quantities, such as precipitation (Min et al. 2011; Pall et al. 2011), humidity (Santer et al. 2007; Willett et al. 2007), pressure (Gillett and Stott 2009), ocean heat content (AchutaRao et al. 2006), and tropospheric and stratospheric temperature (Santer et al. 2012) in addition to surface temperature. Further discussion of attribution is provided in the Appendix.

Natural variations in climate include the effects of the natural cycles mentioned above, plus the 11-year sunspot cycle and other changes in the radiation from the Sun, as well as the effects of volcanic eruptions. Natural variations can be as large as human-induced climate change over timescales of up to a decade or two at the global scale. As a result, global temperature does not always increase steadily, as evidenced, for example, by the period between 1998 and 2007, which showed little change. This time period is too short to signify a change in the warming trend, as climate trends are measured over periods of decades, not years (Easterling and Wehner 2009; Foster and Rahmstorf 2011; Knight et al. 2009; Rahmstorf et al. 2012; Santer et al. 2011). Over the time scale of multiple decades, the human influence has been dominant, and the most recent 10-year period is clearly the hottest on record. Note that changes in temperature at local scales, such as urban areas, can be quite different than those at larger spatial scales, in part because of local land-use patterns.

Box: Models Used in the Assessment

Throughout the 2013 National Climate Assessment report, there are references to projections from models of the physical processes affecting the Earth's climate system. Three distinct sets of model simulations are discussed:

- Climate Model Intercomparison Project, 3rd phase (CMIP3): global model analyses done for the 2007 IPCC assessment. Spatial resolutions typically vary from 125 to 187 miles (at mid-latitudes); approximately 25 representations of different models (not all are used in all studies). CMIP3 findings are the foundation for most of the impact assessments included in this report.
- Climate Model Intercomparison Project, 5th phase (CMIP5): Newer global model analyses done for the 2013 IPCC assessment. Spatial resolutions typically vary from 62 to 125 miles; about 30 representations of different models (not all are used in all studies); this new information was not available in time for it to serve as the foundation for the impacts assessments in this report, and information from CMIP5 is primarily provided for comparison purposes.
- North American Regional Climate Change Assessment Program (NARCCAP): 6 regional climate model analyses (and one global model) for the continental U.S. run at about 30-mile horizontal resolution.

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Ten Indicators of a Warming World

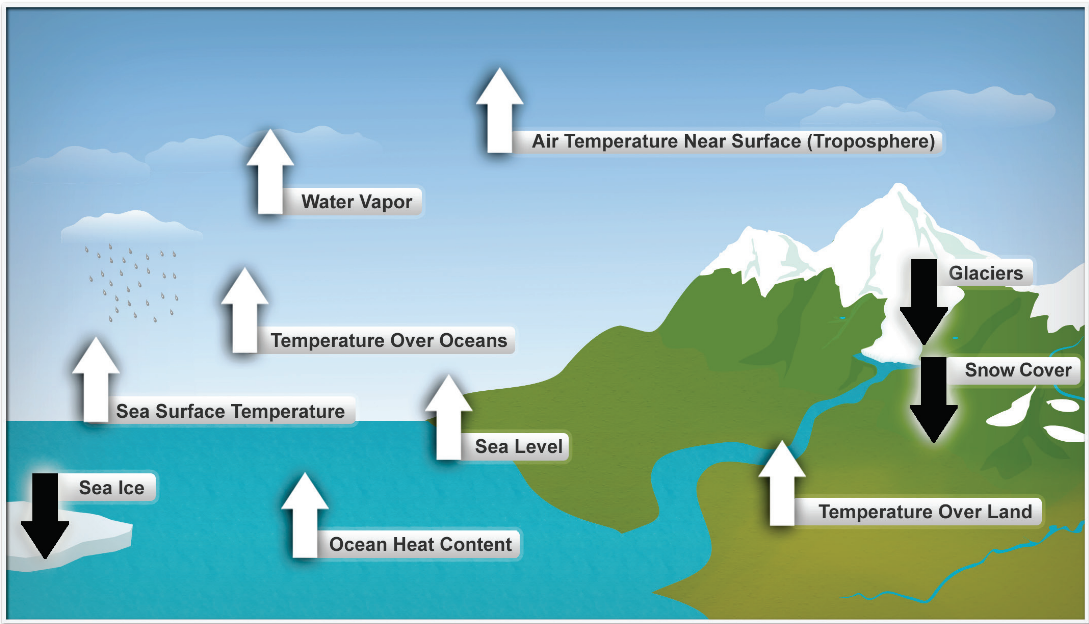

Figure 2.1: Ten Indicators of a Warming World

Caption: These are just some of the many indicators that have been measured globally over many decades and that show that Earth's climate is warming. White arrows indicate increasing trends, black arrows indicate decreasing trends. All the indicators expected to increase in a warming world are increasing, and all those expected to decrease in a warming world are decreasing. (Figure source: NOAA NCDC)

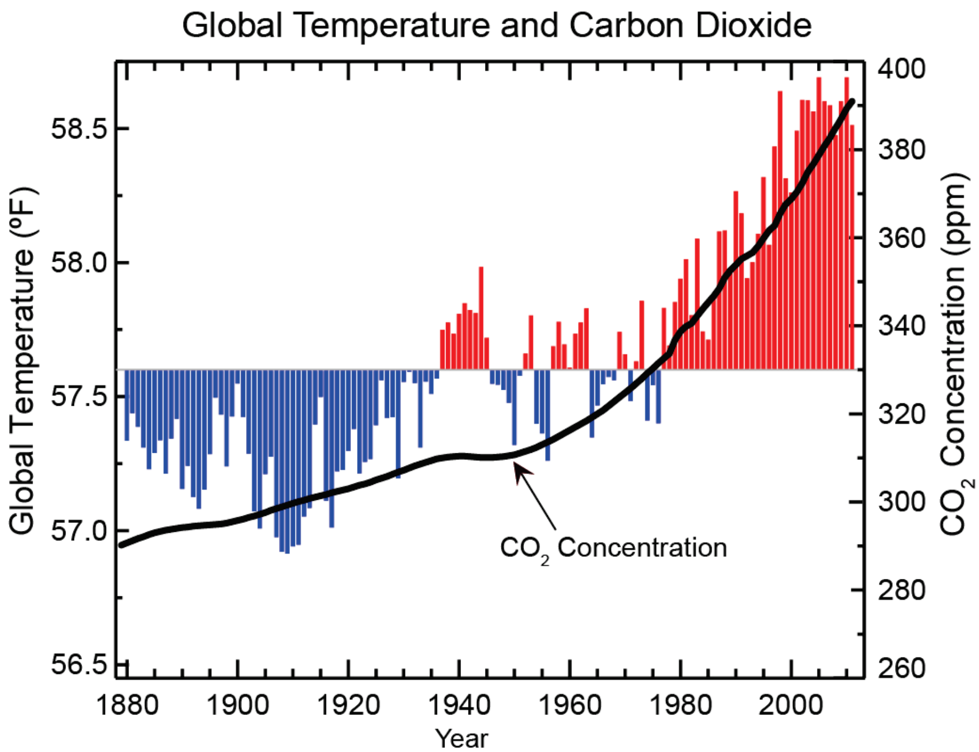

Figure 2.2: Global Temperature and Carbon Dioxide

Caption: Global annual average temperature (as measured over both land and oceans; scale on left) has increased by more than 1.4°F (0.8°C) since 1880. Red bars show temperatures above the long-term average, and blue bars indicate temperatures below the long-term average. The black line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm); scale on right. While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are due to natural processes, such as the effects of El Niños, La Niñas, and the eruption of large volcanoes. (Figure source: NOAA NCDC. Temperature data from NOAA NCDC 2012; CO2 data from NOAA ESRL 2012.)

Future Climate Change

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the climate is to those emissions.

A certain amount of continued warming of the planet is projected to occur as a result of human-induced emissions to date; another 0.5°F increase would occur even if all emissions from human activities were suddenly stopped (Matthews and Zickfeld 2012). However, choices made now and in the next few decades will determine the amount of additional future warming. Beyond mid-century, lower levels of heat-trapping gases in scenarios with reduced emissions will lead to noticeably less future warming. Higher emissions levels will result in more warming, and thus more severe impacts on many aspects of human society and the natural world.

Our confidence in projections of future climate change has increased. The wider range of potential changes in global average temperature in the latest generation of climate model simulations (Taylor et al. 2012) used in the IPCC's current assessment versus those in the previous assessment (IPCC 2007) is simply a result of considering more options for future human behavior. For example, one of the scenarios included in the IPCC's latest assessment assumes aggressive emissions reduction designed to limit the global temperature increase to 3.6°F (2°C) above pre-industrial levels (Schnellnhuber et al. 2006). This path would require emission reductions (more than 70% reduction in human-related emissions by 2050 – see Appendix, Key Message 5) sufficient to achieve heat-trapping gas concentrations well below those of any of the scenarios considered by the IPCC in its 2007 assessment. Such scenarios enable the investigation of climate impacts that would be avoided by deliberate, substantial, and aggressive reductions in heat-trapping gas emissions.

Projections of changes in precipitation largely follow recently observed patterns of change, with overall increases in the global average but substantial shifts in where and how precipitation falls. Generally, areas closest to the poles are projected to receive more precipitation, while the dry belt that lies just outside the tropics (greater than 23°N/S) expands further poleward and receives less rain. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), especially over the tropical Pacific. Certain regions, including the western U.S. (especially the Southwest (Karl et al. 2009)) and the Mediterranean, are already dry and are expected to become drier. The widespread trend toward more heavy downpours is expected to continue, with precipitation becoming less frequent but more intense. The patterns of the projected changes of precipitation do not contain the spatial details that characterize observed precipitation, especially in mountainous terrain, because the projections are averages from multiple models and because the resolution of global climate models is typically about 60 miles.

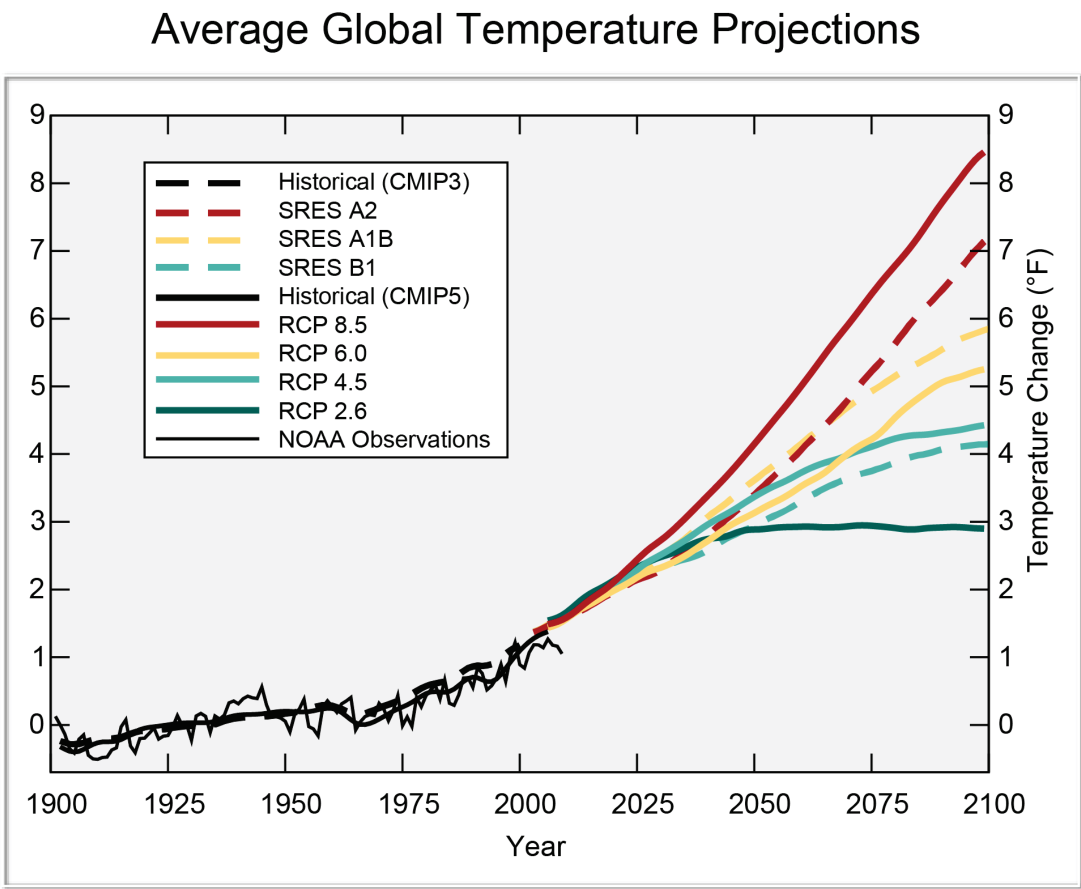

Figure 2.3: Average Global Temperature Projections

Caption: Projected global average annual temperature changes (°F) for multiple future emissions scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models using the previous generation of emissions scenarios (the SRES set). The solid lines are results from the most recent generation of climate models using the most recent emissions scenarios (the RCP set), some of which consider explicit climate policies, which the older ones did not. Differences among these projections are principally a result of differences in the emissions scenarios rather than differences among the climate models. (Figure source: Michael Wehner, LBNL. Data from CMIP3, CMIP5, and NOAA, 2012.)

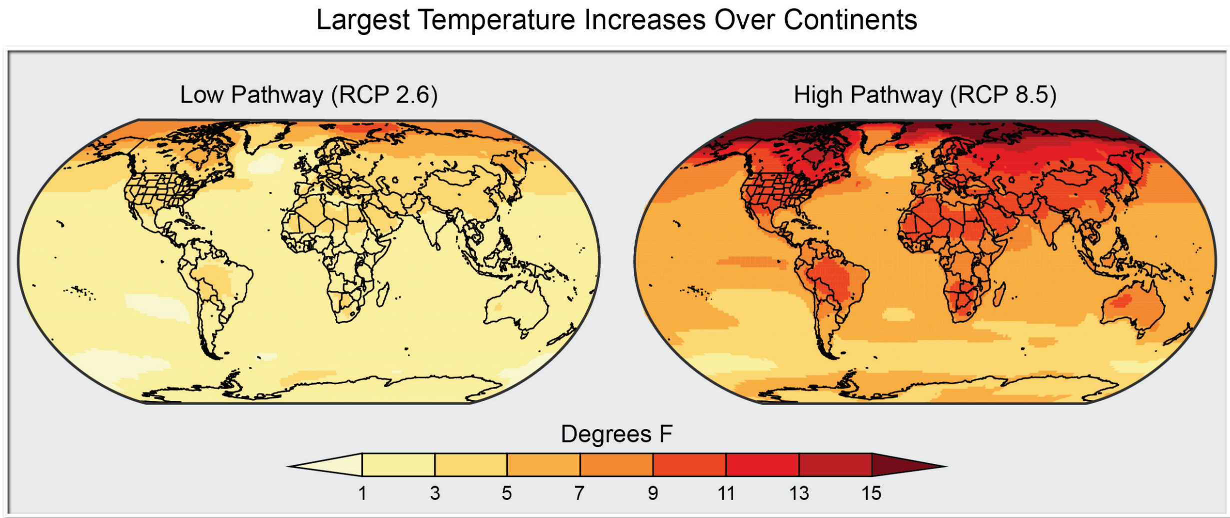

Figure 2.4: Largest Temperature Increases Over Continents

Caption: Projected change (°F) in annual average temperature over the period 2071-2099 (compared to the period 1971-2000) under a low emissions pathway (RCP 2.6, left graph) that assumes rapid reductions in emissions and a high pathway (RCP 8.5, right graph) that assumes continued increases in emissions. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5.)

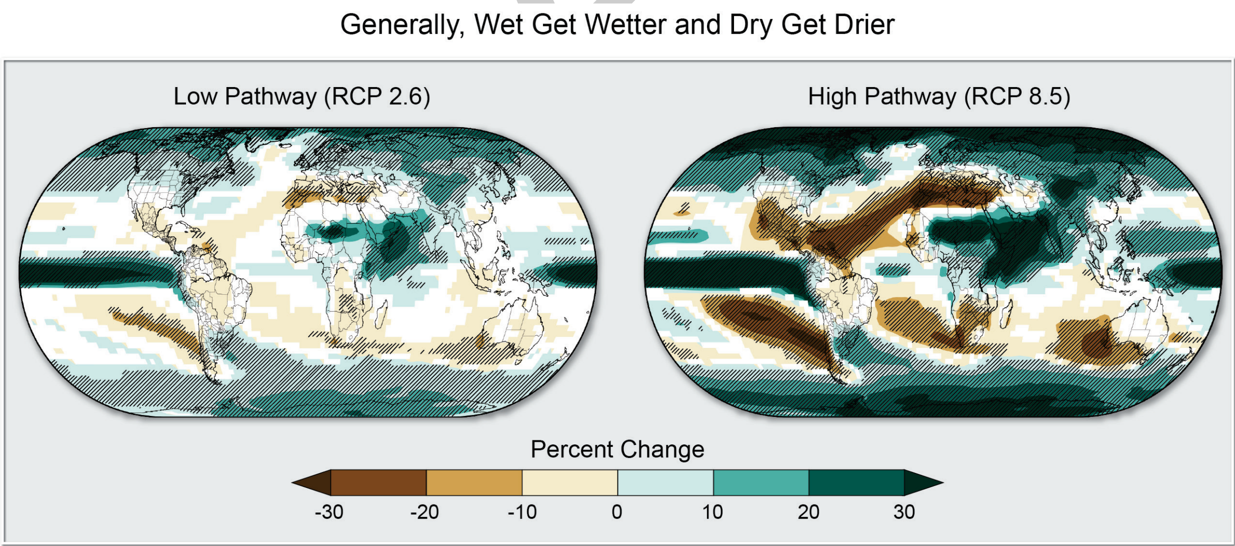

Figure 2.5: Generally, Wet Get Wetter and Dry Get Drier

Caption: Projected percent change in annual average precipitation over the period 2071-2099 (compared to the period 1901-1960) under a low emissions pathway (RCP 2.6) that assumes rapid reductions in emissions and a high pathway (RCP 8.5) that assumes continued increases in emissions. Teal indicates precipitation increases, and brown, decreases. Hatched areas indicate confidence that the projected changes are large and are consistently wetter or drier. White areas indicate confidence that the changes are small. Wet regions generally tend to become wetter while dry regions become drier. In general, the northern parts of the U.S. (especially the Northeast and Alaska) are projected to see more precipitation, while the southern part (especially the Southwest) is projected to see less. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5, analyzed by Michael Wehner, LBNL.) *(note: to be redone with base period 1971-2000)*

Recent U.S. Temperature Trends

U.S. average temperature has increased by about 1.5°F since record keeping began in 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's warmest on record. U.S. temperatures are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, smooth across the country or over time.

There have been substantial advances in our understanding of the U.S. temperature record since the 2009 assessment (Fall et al. 2010; Fall et al. 2011; Karl et al. 2009; Menne and Williams Jr 2009; Menne et al. 2009; Menne et al. 2010; Vose et al. 2012; Williams et al. 2012) (Appendix, Key Message 6 for more information). These advances, together with the continued warming, have strengthened our confidence in, and understanding of the reasons for, the warming. They also confirm that the average annual temperatures have increased over most of the U.S. by about 1.5°F since 1895 (Menne et al. 2009). However, this increase was not constant over time. In particular, temperatures generally rose until about 1940, declined until about 1980, then increased rapidly thereafter, with 80% of the total increase occurring after 1980. Over even shorter time scales up to a decade or more, natural variability (see the Appendix) can reduce the rate of warming or even create a temporary cooling. The cooling in mid-century that was especially prevalent over the eastern half of the U.S. may also have stemmed partly from the cooling effects of sulfate particles from coal burning power plants (Leibensperger et al. 2012), before these sulfur emissions were regulated to address health and acid rain concerns.

Since 1991, temperatures have averaged 1°F to 1.5°F higher than 1901-1960 over most of the U.S., except for the Southeast, where the warming has been less than 1°F. On a seasonal basis, long-term warming has been greatest in winter and spring.

The cooling in mid-century extended over most of the southern and eastern U.S., and temperatures decreased slightly in parts of the Southeast if measured as a trend over the full century 1900-2000 (in contrast to almost all other global land areas, which warmed over that period). Such regional cooling can occur occasionally because natural variations can be larger than human influences over small areas for periods of decades. However, the Southeast has warmed over the past few decades and warming is ultimately projected for all parts of the nation during this century. In the next few decades, this warming will be roughly 2°F to 4°F in most areas. By the end of the century, U.S. warming is projected to correspond closely to the level of global emissions: roughly 3°F to 5°F under lower emissions scenarios (B1 or RCP 4.5) involving substantial reductions in emissions, and 5°F to 10°F for higher emissions scenarios (A2 or RCP 8.5) that assume continued increases in emissions; the largest temperature increases are projected for the upper Midwest and Alaska.

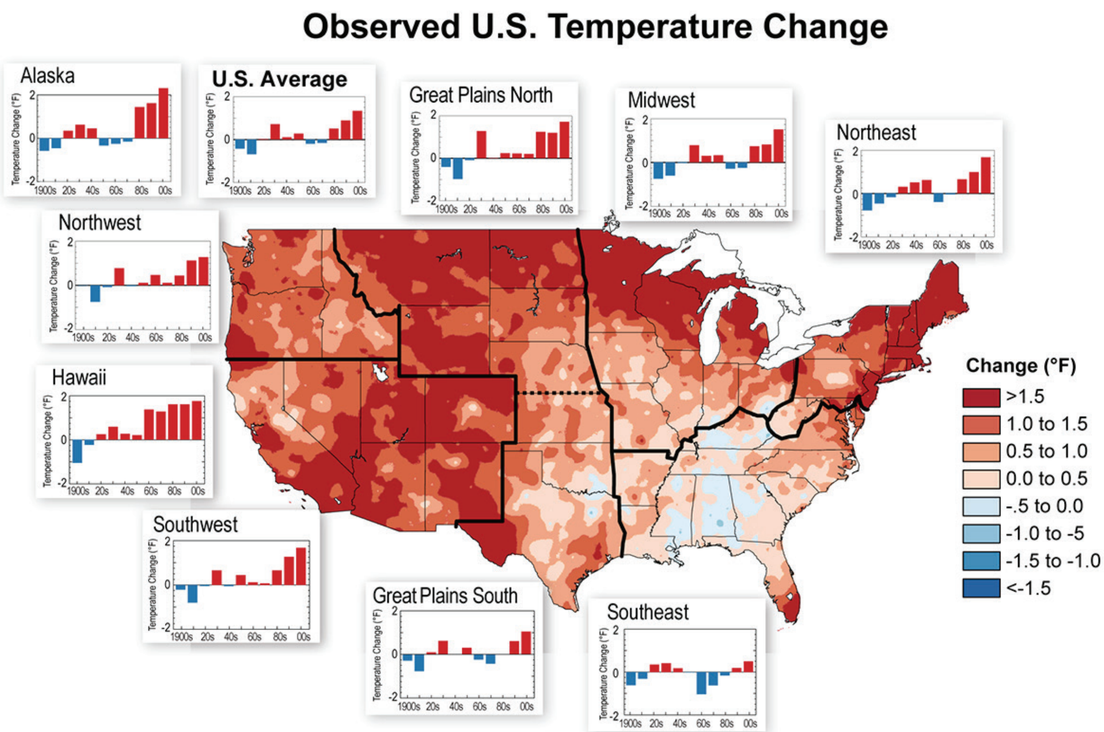

Figure 2.6: Observed U.S. Temperature Change

Caption: The colors on the map show temperature changes over the past 20 years in °F (1991-2011) compared to the 1901-1960 average. The bars on the graphs show the average temperature changes by decade for 1901-2011 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011. The period from 2001 to 2011 was warmer than any previous decade in every region. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

Future human-induced warming depends on both past and future emissions of heat-trapping gases and changes in the amount of particle pollution. The amount of climate change (aside from natural variability) expected for the next two to three decades is a combination of the warming already built into the climate system by the past history of human emissions of heat-trapping gases, and the expected ongoing increases of emissions of those gases. The amount of warming over the next few decades is projected to be similar regardless of emissions scenario. However, the magnitude of temperature increases over the second half of this century, both in the U.S. and globally, will be primarily determined by future emissions, and there are substantial differences between higher, fossil-fuel intensive scenarios compared to scenarios in which emissions are reduced. The most recent model projections of climate change due to human activities expand the range of future scenarios considered (particularly at the lower end), but are entirely consistent with the older model results. This consistency increases our confidence in the projections.

Projected Temperature Change

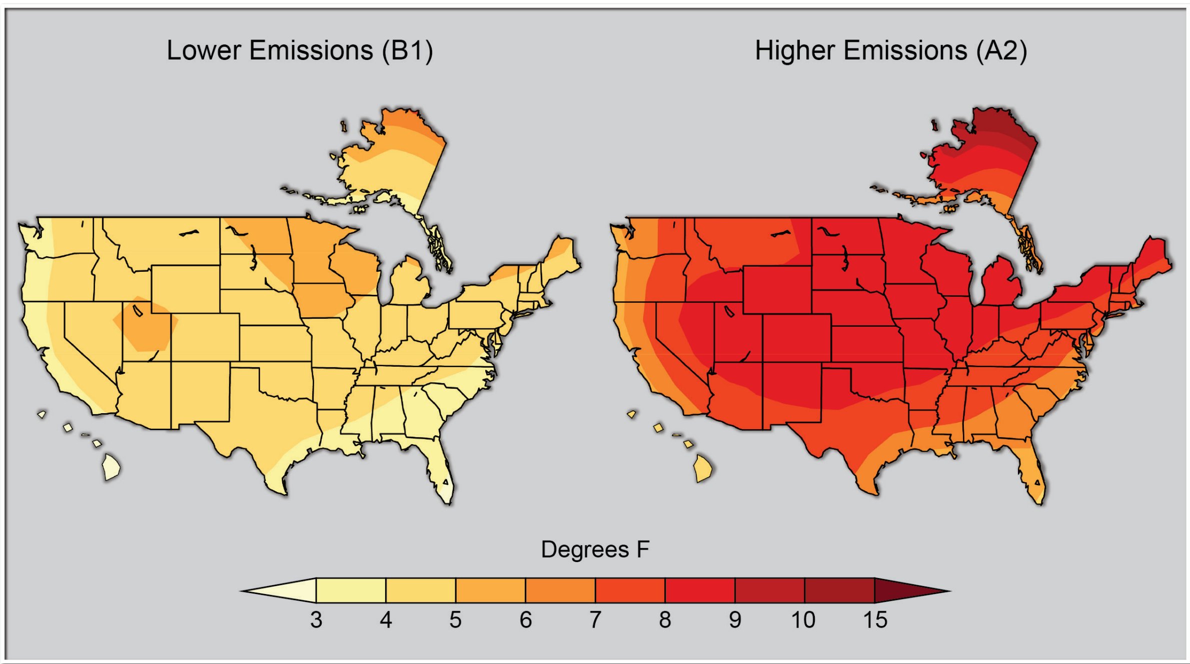

Figure 2.7: Projected Temperature Change

Caption: Maps show projected change in average surface air temperature in the later part of this century (2070-2099) relative to the later part of the last century (1971-1999) under a scenario that assumes substantial reductions in heat trapping gases (B1, left) and a higher emissions scenario that assumes continued increases in global emissions (A2, right). These scenarios are used throughout this report for assessing impacts under lower and higher emissions. Projected changes are averages from 15 CMIP3 models for the A2 scenario and 14 models for the B1 scenario. (See Appendix, Key Message 5 for a discussion of temperature changes under a wider range of future scenarios for various periods of this century). (Figure source: adapted from (Kunkel et al. 2012).)

BOX: Newer Simulations for Projected Temperature (CMIP5 models)

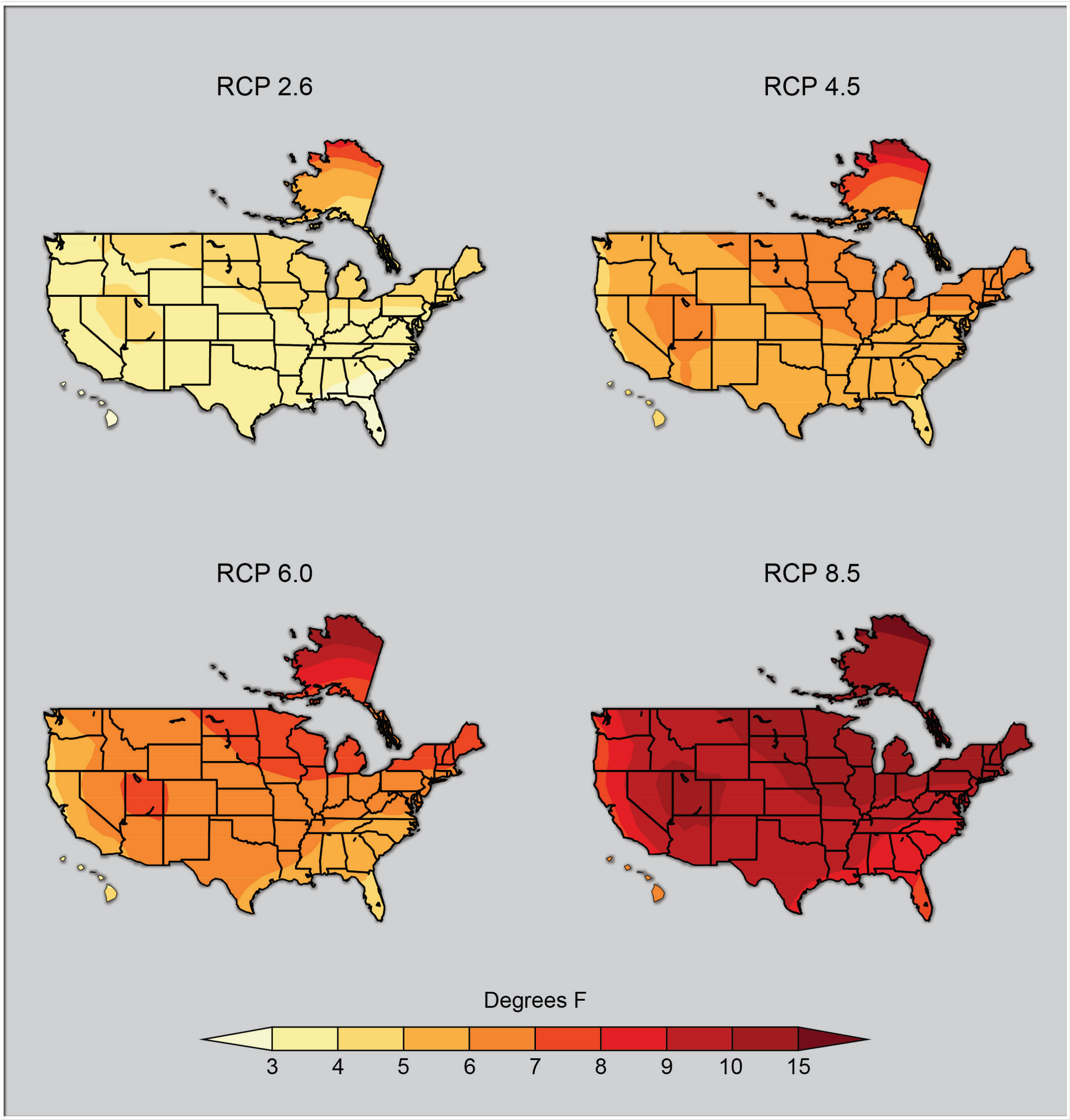

Figure 2.8:

Caption: The largest uncertainty in projecting future climate change is the level of emissions. The most recent model projections (shown above) take into account a wider range of options with regard to human behavior; these include a lower emissions scenario (RCP 2.6, top left) than has been considered before. This scenario assumes rapid reductions in emissions – more than 70% cuts from current levels by 2050 – and the corresponding smaller amount of warming. On the high end, they include a scenario that assumes continued increases in emissions (RCP 8.5, bottom right) and the corresponding greater amount of warming. Also shown are temperature changes (°F) for the intermediate scenarios RCP 4.5 (top right, which is most similar to B1) and RCP 6.0 (bottom left, which is most similar to A1B; see the Appendix). Projections show change in average surface air temperature in the later part of this century (2071-2099) relative to the late part of the last century (1971-2000). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5.)

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Lengthening Frost-free Season

The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s, with the largest increases occurring in the western U.S., affecting ecosystems and agriculture. Continued lengthening of the growing season across the U.S. is projected.

The length of the frost-free season (or growing season, in common usage) is a major determinant of the types of plants and crops that are well-adapted to a particular region. The frost-free season length has been gradually increasing since the 1980s (U.S. Environmental Protection Agency 2010). The last occurrence of 32°F in the spring has been occurring earlier in the year, and the first occurrence of 32°F in the fall has been happening later. During 1991-2011, the average frost-free season was about 10 days longer than during 1901-1960. These observed climate changes have been mirrored by changes in the biosphere, including increases in forest productivity (Dragoni et al. 2011), satellite estimates of the length of the growing season (Jeong et al. 2011), and length of the ragweed pollen season (Ziska et al. 2011). A longer growing season can mean greater evaporation and loss of moisture through plant transpiration associated with higher temperatures so that even with a longer frost-free season, crops could be negatively affected by drying. Likewise, increases in forest productivity can be offset by drying, leading to an earlier and longer fire season and more intense fires.

The lengthening of the frost-free season has been somewhat greater in the western U.S. than the eastern U.S. (Karl et al. 2009), increasing by 2 to 3 weeks in the Northwest and Southwest, 1 to 2 weeks in the Midwest, Great Plains, and Northeast, and slightly less than 1 week in the Southeast. These differences mirror the overall trend of more warming in the north and west and less warming in the Southeast.

In a future in which heat-trapping gas emissions continue to grow, increases of a month or more in the lengths of the frost-free and growing seasons are projected across most of the U.S. by the end of the century, with slightly smaller increases in the northern Great Plains. The largest increases in the frost-free season (more than 8 weeks) are projected for the western U.S., particularly in high elevation and coastal areas, consistent with rising sea surface temperatures. The increases would be considerably smaller if heat-trapping gas emissions are reduced, although still substantial. These increases are projected to be much greater than the normal year-to-year variability experienced today. The projected changes also imply that the southern boundary of the seasonal freeze zone will move north, with increasing frequencies of years without subfreezing temperatures in the most southern parts of the U.S.

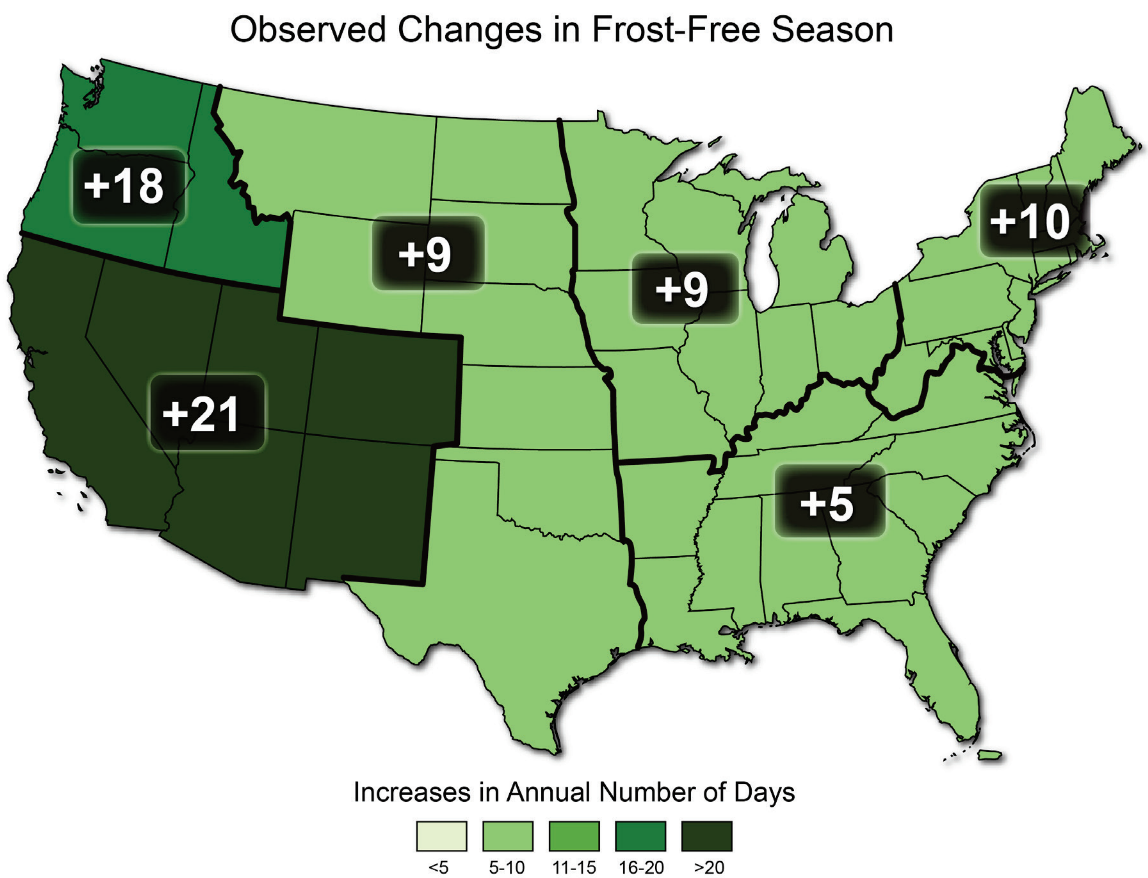

Figure 2.9: Observed Changes in Frost-Free Season

Caption: The frost-free season length, defined as the period between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has increased in each U.S. region during 1991-2011 relative to 1901-1960. Increases in frost-free days correspond to similar increases in growing season length. (Figure source: NOAA/NCDC / CICS-NC. Data from Kunkel et al. 2012a, 2012b, 2012c, 2012d, 2012e, 2012f).

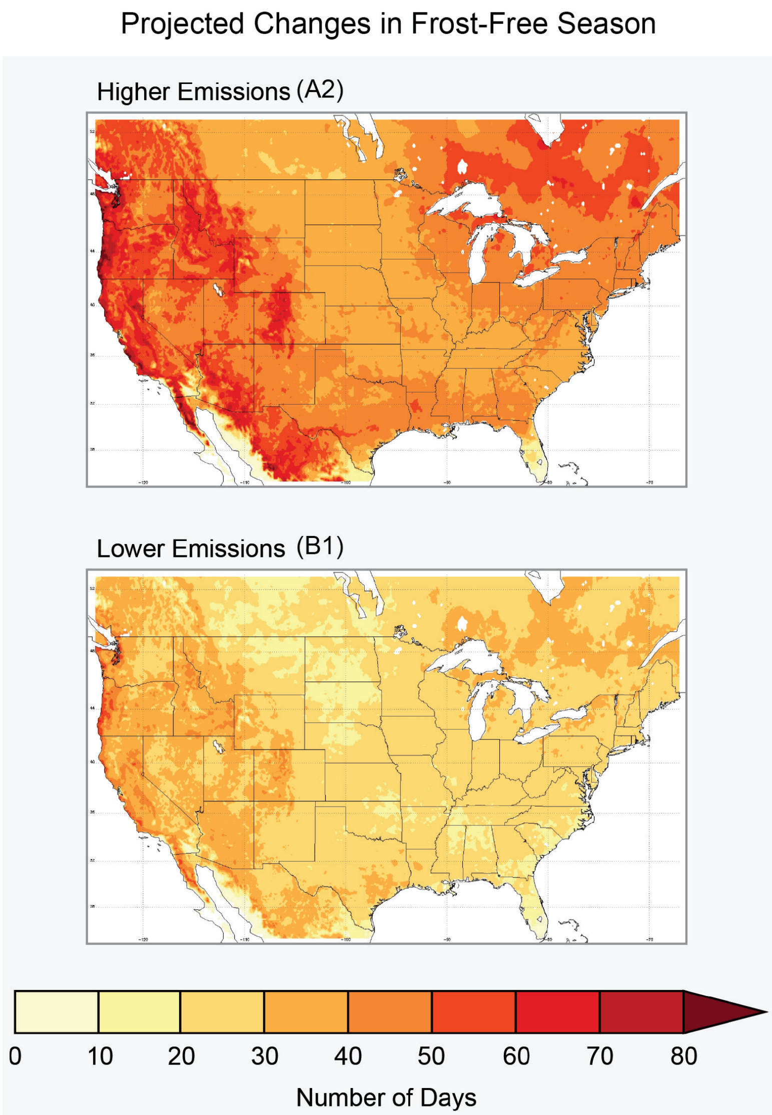

Figure 2.10: Projected Changes in Frost-Free Season

Caption: The maps show projected increases in frost-free days for the last three decades of this century (2070-2099 as compared to 1971-2000) under two emissions scenarios, one in which heat-trapping gas emissions continue to grow (A2, top map) and one in which emissions are rapidly reduced (B1, bottom map). Increases in the frost-free season correspond to similar increases in the growing season. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Statistically Downscaled; Hayhoe et al. 2008; Hayhoe et al. 2004; Kunkel et al. 2012)

U.S. Precipitation Change

Precipitation averaged over the entire U.S. has increased during the period since 1900, but regionally some areas have had increases greater than the national average, and some areas have had decreases. The largest increases have been in the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century.

Since 1900, average annual precipitation over the U.S. has increased by roughly 5%. This increase reflects, in part, the major droughts of the 1930s and 1950s, which made the early half of the record drier. There are important regional differences. For instance, precipitation since 1991 (relative to 1901-1960) increased the most in the Northeast (8%), Midwest (9%), and southern Great Plains (8%), while much of the Southeast and Southwest had a mix of areas of increases and decreases (McRoberts and Nielsen-Gammon 2011; Peterson et al. 2012).

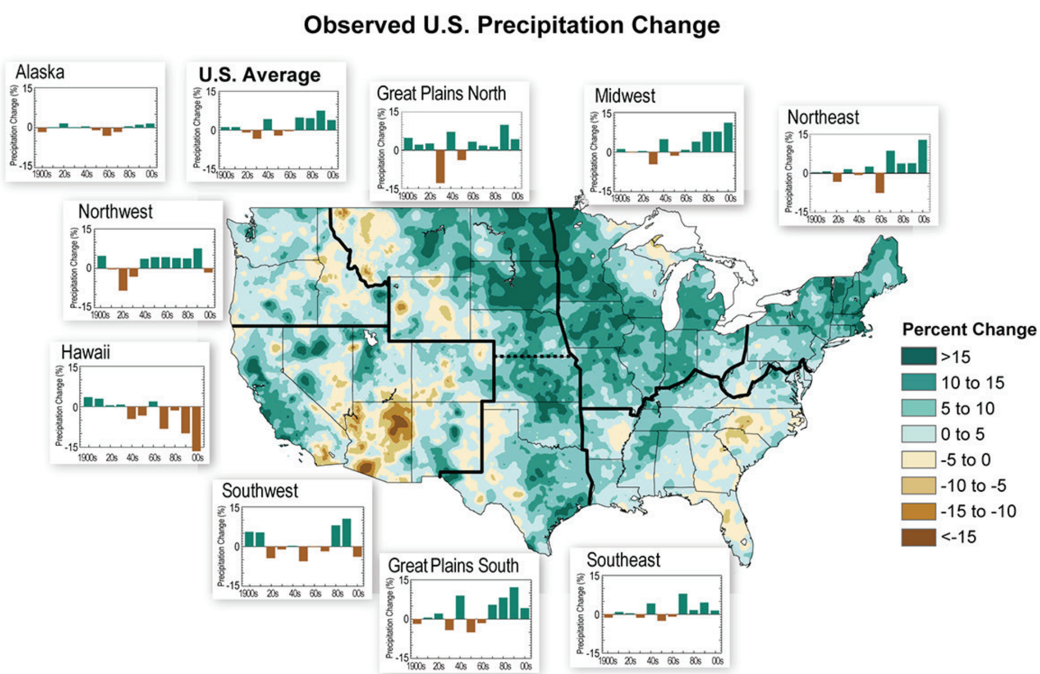

Figure 2.11: Observed U.S. Precipitation Change

Caption: The colors on the map show annual total precipitation changes (percent) for 1991-2011 compared to the 1901-1960 average, and show wetter conditions in most areas (McRoberts and Nielsen-Gammon 2011). The bars on the graphs show average precipitation differences by decade for 1901-2011 (relative to the 1901-1960 average) for each region. The far right bar is for 2001-2011. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

While significant trends in average precipitation have been detected, the fraction of these trends attributable to human activity is difficult to quantify because the range of natural variability in precipitation is large. However, if emissions of heat-trapping gases continue their upward trend, clear patterns of precipitation change are projected to emerge. The northern U.S. is projected to experience more precipitation in the winter and spring (except for the Northwest in the spring), while the Southwest is projected to experience less, particularly in the spring.

The projected changes in the northern U.S. are a consequence of both a warmer atmosphere and associated large-scale circulation changes. Warmer air can hold more moisture than colder air, leading to more intense rainfall. The projected reduction in Southwest precipitation is a result of large-scale circulation changes caused by increased heating of the global atmosphere. Recent improvements in the understanding of these mechanisms of change increase confidence in these projections (Held and Soden, 2008). The patterns of the projected changes of precipitation resulting from human alterations of the climate are geographically smoother in these maps than what will actually be observed because: 1) natural variations can not be projected far into the future; and 2) current climate models are too coarse to capture fine topographic details, especially in mountainous terrain. Hence, there is considerably more confidence in the large-scale patterns of change than in the small details.

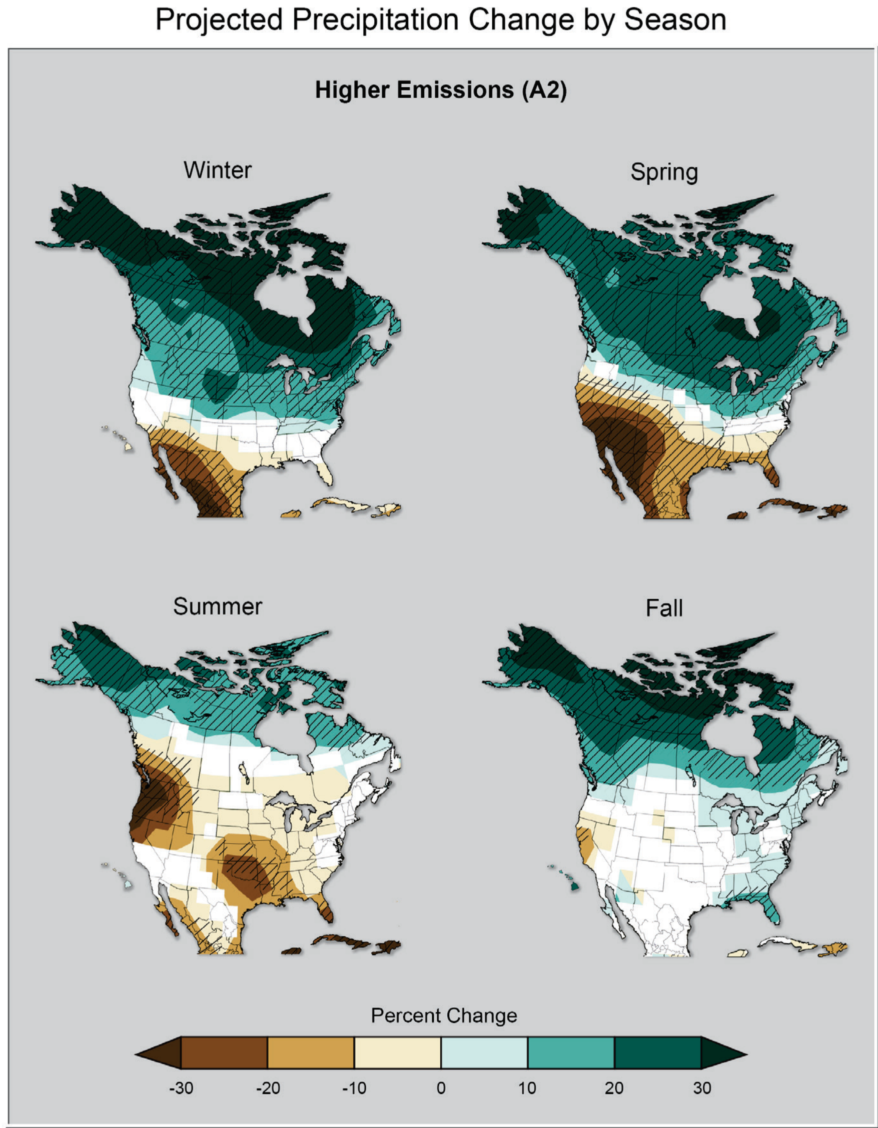

Figure 2.12: Projected Precipitation Change by Season

Caption: Projected percent change in seasonal precipitation for 2070-2099 (compared to the period 1901-1960) under an emissions scenario that assumes continued increases in emissions (A2). Teal indicates precipitation increases, and brown, decreases. Hatched areas indicate confidence that the projected changes are large and are consistently wetter or drier. White areas indicate confidence that the changes are small. Wet regions tend to become wetter while dry regions become drier. In general, the northern part of the U.S. is projected to see more winter and spring precipitation, while the Southwest is projected to experience less precipitation in the spring. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3; analyzed by Michael Wehner, LBNL.) *(note: to be redone with base period 1971-2000)*

In general, a comparison of the various sources of climate model data used in this assessment provides a consistent picture of the large-scale projected precipitation changes across the U.S. These include the global models used in the Coupled Model Intercomparison Project, versions 3 and 5 (CMIP3, CMIP5) as well as the suite of regional models (from the North American Regional Climate Change Assessment Program, NARCCAP). Multi-model average changes in all three of these sources show a general pattern of wetter future conditions in the north and drier conditions in the south, but the regional suite generally shows conditions that are overall somewhat wetter in the wet areas and not as dry in the dry areas. The general pattern agreement among these three sources, with the wide variations in their spatial resolution, provides confidence that this pattern is robust and not sensitive to the limited spatial resolution of the models. The slightly different conditions in the North American NARCCAP regional suite for the U.S. appear to arise partially or wholly from the choice of the four global climate models used to drive the regional simulations. These four models, averaged together, project average changes that are slightly (2%) wetter than the average of the suite of global models used in CMIP3.

The patterns of precipitation change in the newer CMIP5 simulations are essentially the same as in the earlier CMIP3 and NARCCAP simulations used in impact analyses throughout this report, increasing confidence in our scientific understanding. The subtle differences between these two sets of projections are mostly due to the wider range of future emissions scenarios considered in the more recent simulations. Thus, the overall picture remains the same: wetter conditions in the north and drier conditions in the Southwest in the winter and spring. Drier conditions in the summer are projected in most areas of the contiguous U.S. but, outside of the Northwest and south-central region, there is generally not high confidence that the changes will be large compared to natural variability. In all models and scenarios, a transition zone between drier (to the south) and wetter (to the north) shifts northward from the southern U.S. in winter to southern Canada in summer. Wetter conditions are projected for Alaska and northern Canada in all seasons.

BOX: Newer Simulations for Projected Precipitation Change (CMIP5 models)

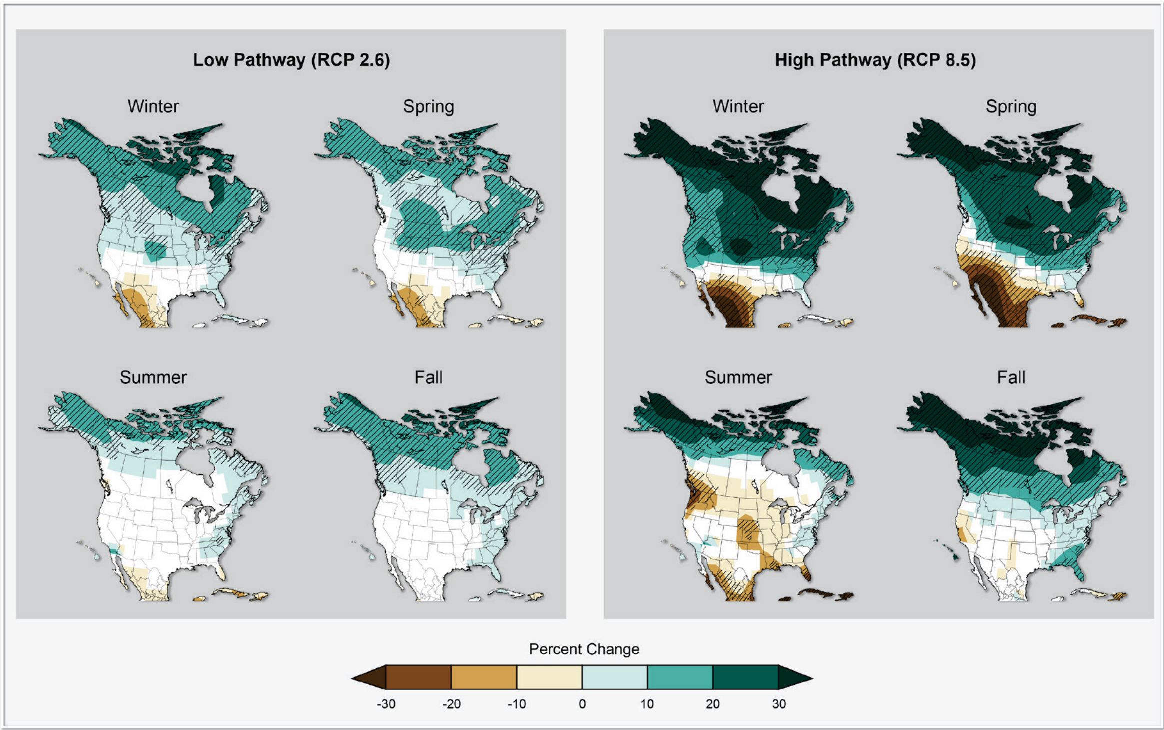

Figure 2.13

Projected seasonal precipitation change (percent) for 2071-2099 (compared to 1901-1960) as projected by recent simulations that include a wider range of emissions scenarios. The maps on the left (RCP 2.6) assume rapid reductions in emissions – more than 70% cuts from current levels by 2050 – and a corresponding much smaller amount of warming and far less precipitation change. On the right, RCP 8.5 assumes continued increases in emissions, with associated large increases in warming and major precipitation changes. These would include, for example, large reductions in spring precipitation in the Southwest and large increases in the Northeast and Midwest. Rapid emissions reductions could be expected to yield the more modest changes in the maps on the left. In these seasonal projections, teal indicates precipitation increases, and brown, decreases. Hatched areas indicate confidence that the projected changes are large and are consistently wetter or drier. White areas indicate confidence that the changes are small. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5; analyzed by Michael Wehner, LBNL.) *(note: to be redone with base period 1971-2000)*

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Heavy Downpours Increasing

Heavy downpours are increasing in most regions of the U.S., especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas.

Across most of the U.S., the heaviest rainfall events have become heavier and more frequent. The amount of rain falling on the heaviest rain days has also increased over the past few decades. Since 1991, the amount of rain falling in very heavy precipitation events has been above average in every region of the country, except Hawaii. This increase has been greatest in the Northeast, Midwest, and Great Plains – more than 30% above the 1901-1960 average (Karl et al. 2009). There has also been an increase in flooding events in the Midwest and Northeast where the largest increases in heavy rain amounts have occurred.

Warmer air can contain more water vapor than cooler air. Global analyses show that the amount of water vapor in the atmosphere has in fact increased over both land and oceans (Dai 2006; Simmons et al. 2010; Willett et al. 2008). Climate change also alters dynamical characteristics of the atmosphere that in turn affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an upward trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms (Kunkel et al. 2012h).

Projections of future climate over the U.S. suggest that the recent trend towards a greater percentage of precipitation falling in heavy rain events will continue. In regions of increasing precipitation, such as the northern U.S., increasingly large percentages of the total precipitation will come from heavy downpours. In these areas, heavy-precipitation events that are presently rare will become more common in the future. Moreover, heavy downpours will account for increasingly large portions of the total precipitation in regions such as the Southwest, where total precipitation is projected to decrease (Kunkel et al. 2012h; Wehner 2012; Wuebbles et al. 2012).

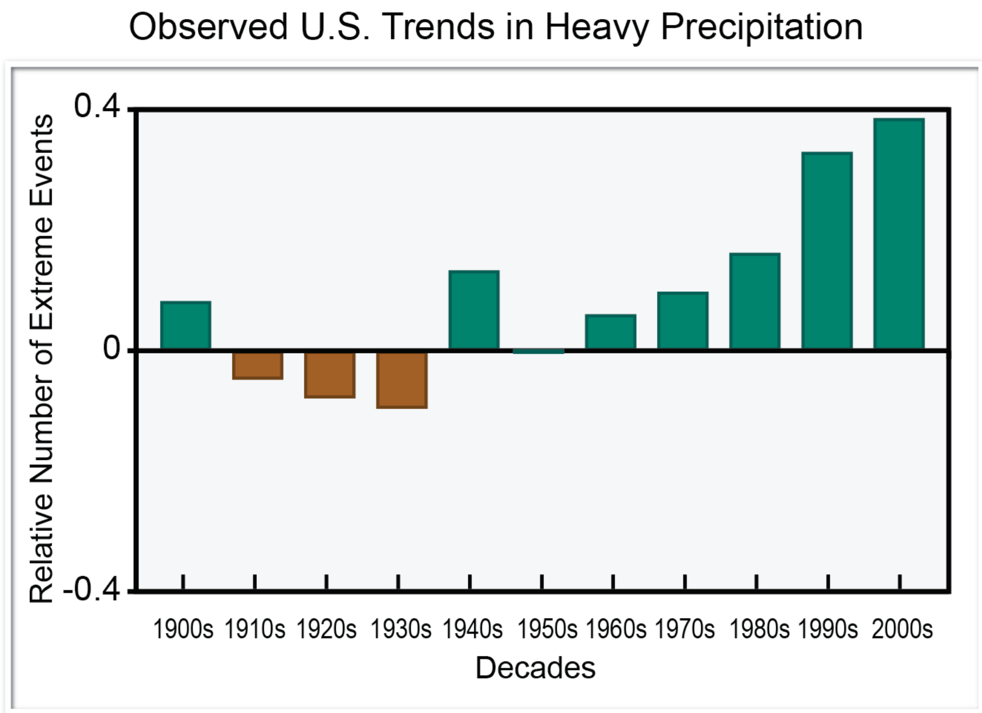

Figure 2.14: Observed U.S. Trends in Heavy Precipitation

Caption: One measure of a heavy-precipitation event is a 2-day precipitation total that is exceeded on average only once in a five year period, also known as the once-in-five-year event. As this extreme precipitation index for 1901-2011 shows, the occurrence of such events has become much more common in recent decades. Changes are compared to the period 1901-1960 and do not include Alaska or Hawaii. The 2000s decade (far right bar) includes 2001-2011. (Figure source: adapted from (Kunkel et al. 2012)

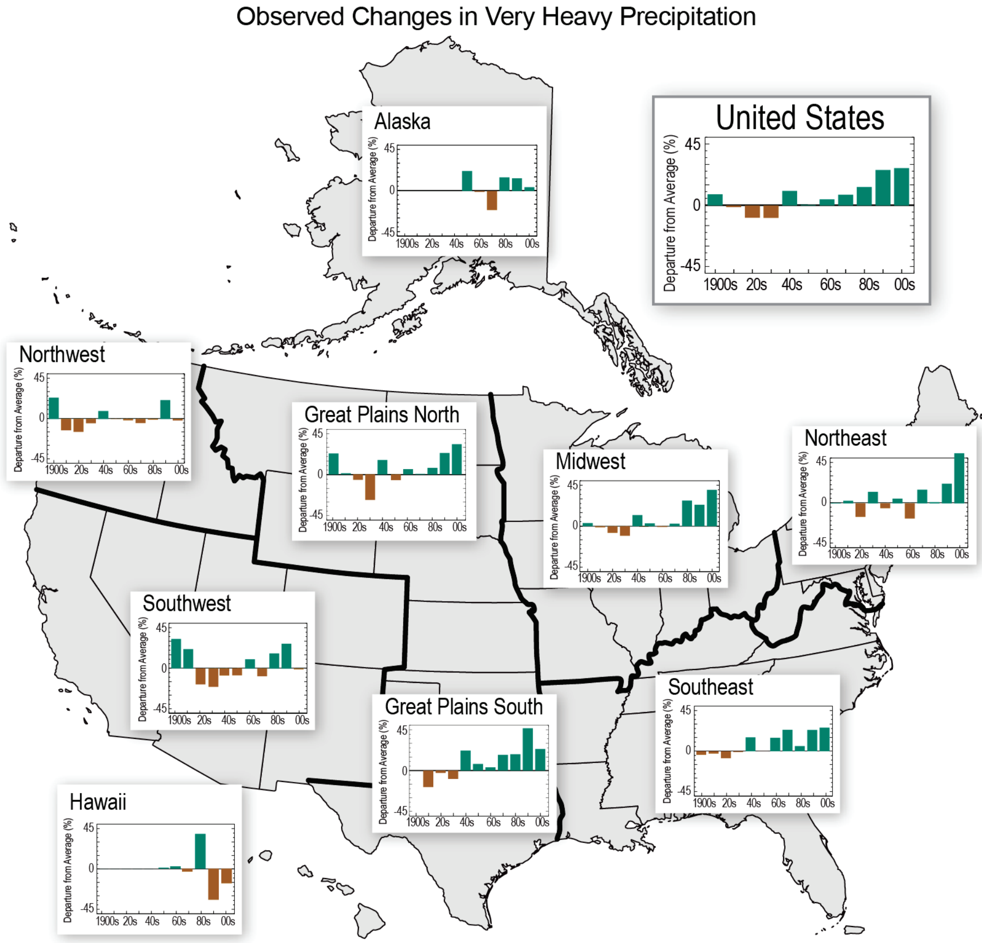

Figure 2.15: Observed Changes in Very Heavy Precipitation

Caption: Percent changes in the annual amount of precipitation falling in *very heavy* events, defined as the heaviest 1% of all daily events from 1901 to 2011 for each region. The far right bar is for 2001-2011. In recent decades there have been increases everywhere, except for the Southwest, Northwest, and Hawaii, with the largest increases in the Northeast, Great Plains, Midwest, and Southeast. Changes are compared to the 1901-1960 average for all regions except Alaska and Hawaii, which are relative to the 1951-1980 average. (Figure source: NOAA NCDC / CICS-NC)

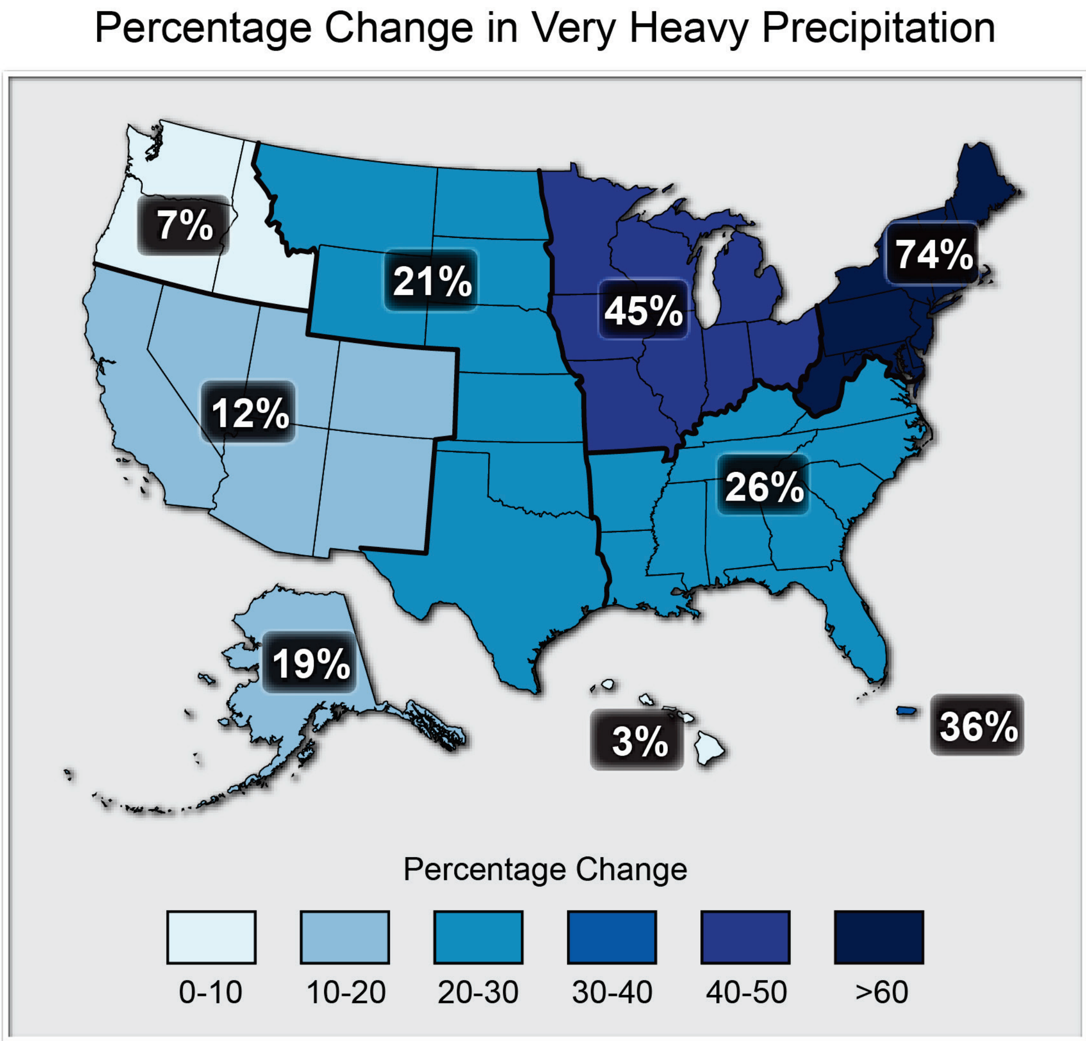

Figure 2.16: Percentage Change in Very Heavy Precipitation

Caption: The map shows percent increases in the amount of precipitation falling in *very heavy* events (defined as the heaviest 1% of all daily events) from 1958 to 2011 for each region. There are clear trends toward a greater amount of *very heavy* precipitation for the nation as a whole, and particularly in the Northeast and Midwest. (Figure source: updated from (Karl et al. 2009) with data from NCDC)

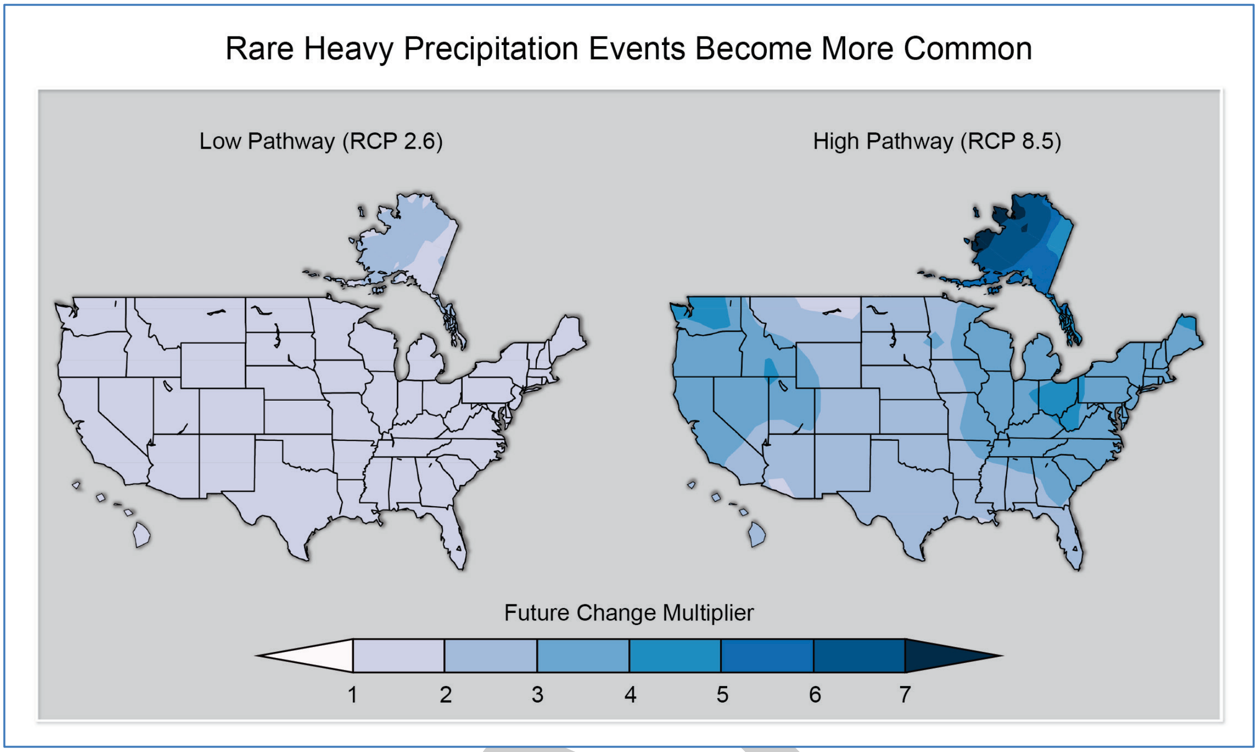

Figure 2.17: Rare Heavy Precipitation Events Become More Common

Caption: Maps show the increase in frequency of extreme daily precipitation events (now occurring about once every twenty years) by the later part of this century (2081-2100) compared to later part of last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the U.S. Under the rapid emissions reduction scenario (RCP 2.6, left), these events would occur up to about twice as often. For the scenario assuming continued increases in emissions (RCP 8.5, right), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5; analysis by Michael Wehner, LBNL; based on methods from (Kharin et al. submitted)

Extreme Weather

Certain types of extreme weather events have become more frequent and intense, including heat waves, floods, and droughts in some regions. The increased intensity of heat waves has been most prevalent in the western parts of the country, while the intensity of flooding events has been more prevalent over the eastern parts. Droughts in the Southwest and heat waves everywhere are projected to become more intense in the future.

Heat waves are periods of abnormally and uncomfortably hot weather lasting days to weeks (Kunkel et al. 1999). Heat waves have generally become more frequent across the U.S. in recent decades, with western regions (including Alaska) setting records for numbers of these events in the 2000s. Tree ring data suggests that the drought over the last decade in the western U.S. represents the driest conditions in 800 years (Karl et al.

2009; Schwalm et al. 2012). Most other regions in the country had their highest number of short-duration heat waves in the 1930s, when the multi-year severe drought of the Dust Bowl period, combined with deleterious land-use practices (Cook et al. 2009), contributed to the intense summer heat through depletion of soil moisture and reduction of the moderating effects of evaporation (Kunkel et al. 2008). However, recent prolonged (multi-month) extreme heat has been unprecedented. The 2011 and 2012 events set records for highest monthly average temperatures, exceeding in some cases records set in the 1930s, including the highest monthly temperature on record (July 2012, breaking the July 1936 record); for the spring and summer months, 2012 had the largest area of record-setting monthly average temperatures, including both hot daytime maximum temperatures and warm nighttime minimum temperatures (Karl et al. 2012). Corresponding with this increase in extreme heat, the number of cold waves has reached the lowest levels on record.

In the past 3 to 4 decades in the U.S. the ratio of record daily high temperatures to record daily low temperatures has steadily increased (also see Meehl et al. 2009). This ratio is now higher than in the 1930s, mostly due to the rapidly declining number of low temperature records. During this same period there has been an increasing trend in persistently high nighttime temperatures (Karl et al. 2009). In some areas, prolonged periods of record high temperatures associated with droughts contribute to dry conditions that are driving wildfires (Trenberth 2011). Numerous studies have documented that human-induced climate change has increased the frequency and severity of heat waves across the globe (Christidis et al. 2011; Stott et al. 2010).

There is emerging evidence that most of the increases of heat wave severity over the U.S. are likely due to human activity (Hansen et al. 2012; Meehl et al. 2007);, with a detectable human influence in recent heat waves in the southern Great Plains (Karl et al. 2009; Rupp et al. 2012) as well as in Europe (Stott et al. 2010; Trenberth 2011), and Russia (Christidis et al. 2011; Duffy and Tebaldi 2012; Meehl et al. 2009). Research has found that the human contribution to climate change approximately doubled the probability of the record heat in Texas in the summer of 2011 (Hoerling et al. 2012a). So while this Texas heat wave and drought could have occurred naturally, the likelihood of record-breaking temperature extremes has increased and will continue to increase as the global climate warms. Generally, the changes in climate are increasing the likelihood for these types of severe events.

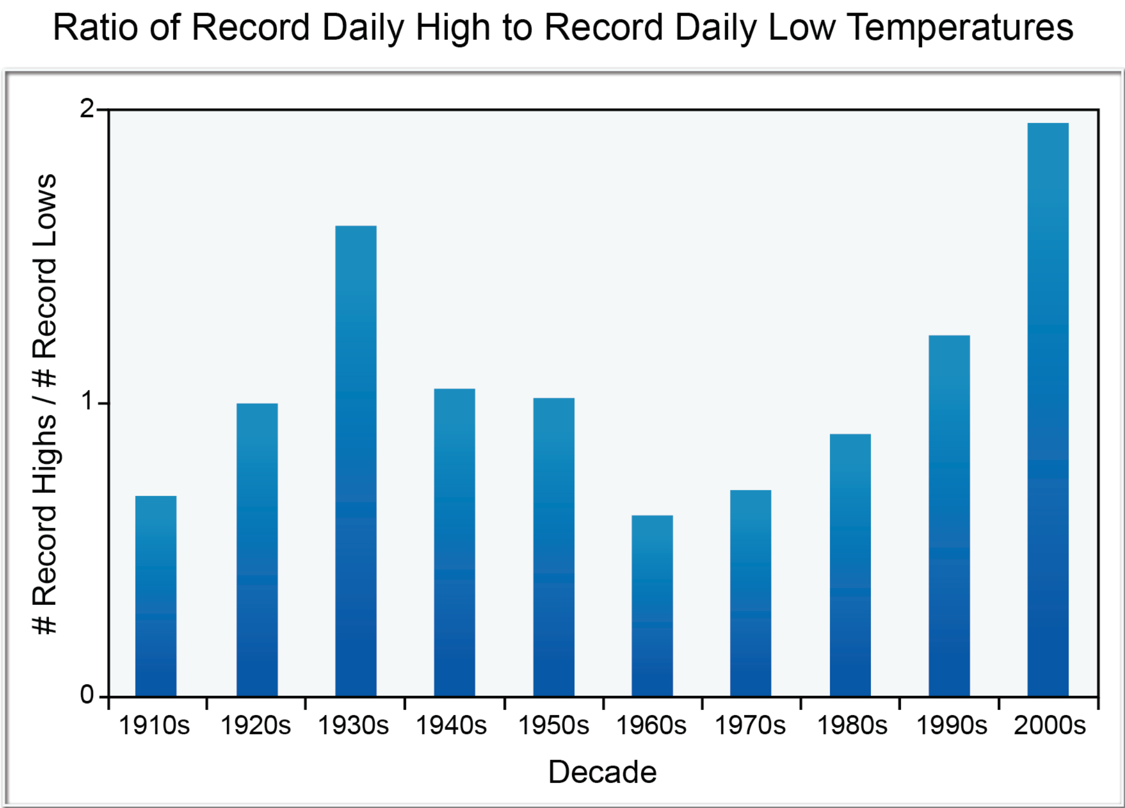

Figure 2.18: Ratio of Record Daily High to Record Daily Low Temperatures

Caption: The ratio of record daily high temperatures to record daily lows for 1911-2010 (relative to the entire history of observations) at about 1,800 weather stations in the 48 contiguous United States has increased from about 1:1 in the 1950s to about 2:1 in the most recent decade, and is higher than the ratio of 1.6:1 in the 1930s, primarily due to very small numbers of low temperature records. The ratios were even higher in 2011 and 2012, which are not shown here. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

Expectations for future heat wave occurrences in the U.S. are shaped by two important considerations. First, the average as well as extreme summer temperatures occurring during individual years of the past decade have approached or exceeded those of the decade of the 1930s over much of the U.S; hence summer temperatures are already moving out of their historical bounds. Second, summer drying is projected for much of the western and central U.S. As discussed below, drying exacerbates heat waves. Accordingly, the number of extremely hot days is projected to continue to increase dramatically over much of the U.S., especially by late century. Climate models project that the same summertime temperatures that ranked among the hottest 5% in 1950-1979 will occur at least 70% of the time by 2035-2064 in the U.S. if global emissions of heat-trapping gases continue to grow (as in the A2 scenario) (Duffy and Tebaldi 2012). By the end of this century, what have previously been once-in-20-year heat waves (4-day events) are projected to occur every two or three years over most of the U.S. (Karl et al. 2008). In other words, what now seems like an extreme heat wave will become commonplace. Confidence has risen in computer model projections because recent observations are consistent with past model projections.

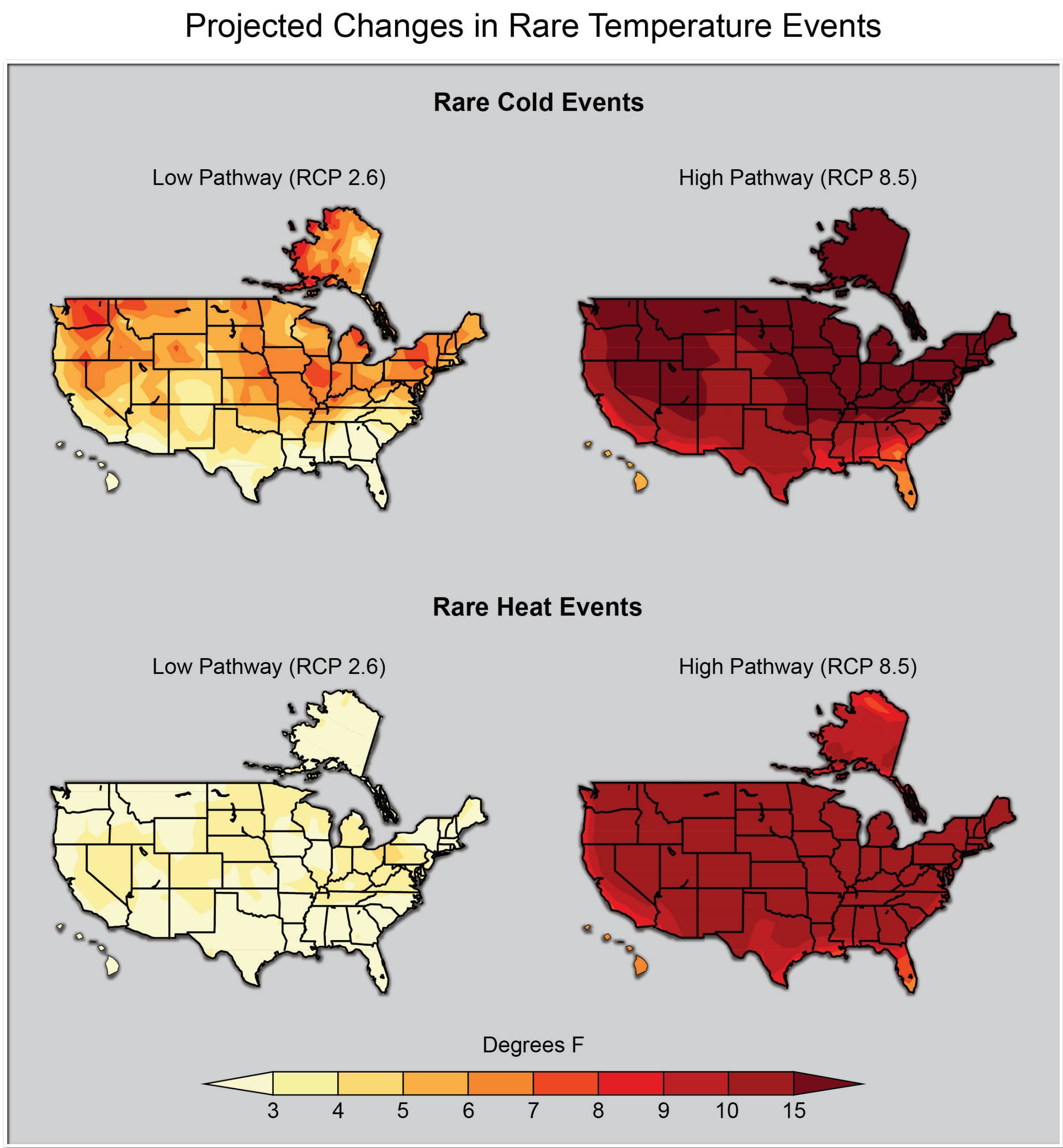

Figure 2.19: Projected Change in Rare Temperature Events

Caption: These maps show that both the hottest and coldest days are projected to be warmer. They show the projected changes in surface air temperature at the end of this century (2081-2100) relative to the end of the last century (1981-2000) on very rare cold and hot days, under a scenario that assumes rapid reductions in emissions (RCP 2.6, left) and a scenario that assumes continued increases in emissions (RCP 8.5, right). In this analysis, very rare cold and hot days are defined as those having a 5% chance of occurring during any given year. The projected temperature increases on such very cold days as well as for very hot days are larger than for the average temperature. In particular, the largest temperature increases will be on rare cold days meaning that bitter cold winter days will be much less frequent across most of the contiguous U.S. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP5; analysis by Michael Wehner, LBNL; based on method from (Kharin et al. submitted).)

In the U.S., flooding in the northern half of the eastern Great Plains and much of the Midwest has been increasing, especially over the last several decades. Flooding has decreased in the Southwest, although there have been small increases in other western states. In the areas of increased flooding, increases in both total precipitation and extreme precipitation are contributing to the flooding increases. Attribution of flood events is a relatively new area of research. There is evidence of a detectable human influence in the timing and magnitude of snowmelt and resulting streamflow in some western U.S. states (Barnett et al. 2008; Hidalgo et al. 2009; Pierce et al. 2008), in recent flooding events in England and Wales (Pall et al. 2011), and in other specific events around the globe during 2011 (Peterson et al. 2012). In general, heavier rains lead to a larger fraction of rainfall running off and, depending on the situation, more potential for flooding. While a 2-inch rain may not cause major impacts in the Southeast where such an event can occur several times a year, it can be disastrous if it occurs in the northern Great Plains.

Trends in Flood Magnitude

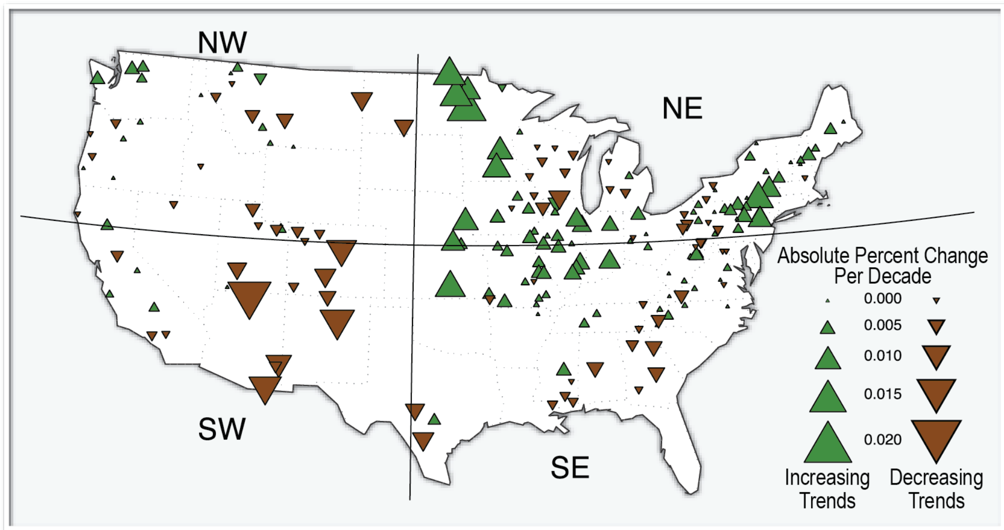

Figure 2.20: Trends in Flood Magnitude

Caption: Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. (Source: Hirsch and Ryberg 2012).

Projected higher temperatures cause increases in evaporation and loss of moisture through plant leaves, leading to drier soils. Precipitation has already declined in some areas within the Southwest and the Rocky Mountain states, and decreases in precipitation are projected to intensify in those areas and spread northward and eastward in summer (see Key Message 5). However, even in areas where precipitation does not decrease, projected higher air temperatures will cause increases in surface evaporation and loss of water from plants, leading to drier soils. As soil dries out, a larger proportion of the incoming heat from the sun goes into heating the soil and adjacent air rather than evaporating its moisture, resulting in hotter summers under drier climatic conditions (Mueller and Seneviratne 2012). Under higher emissions scenarios, widespread drought is projected to become more common over most of the central and southern U.S. (Cayan et al. 2010; Dai 2012; Hoerling et al. 2012b ; Liang et al. 1996; Liang et al. 1994; Maurer et al. 2002; Nijssen et al. 1997; Schwalm et al. 2012; Wehner et al. 2011; Wood and Lettenmaier 2006; Wood et al. 2005)

Extreme Drought in the U.S. and Mexico, Past and Future

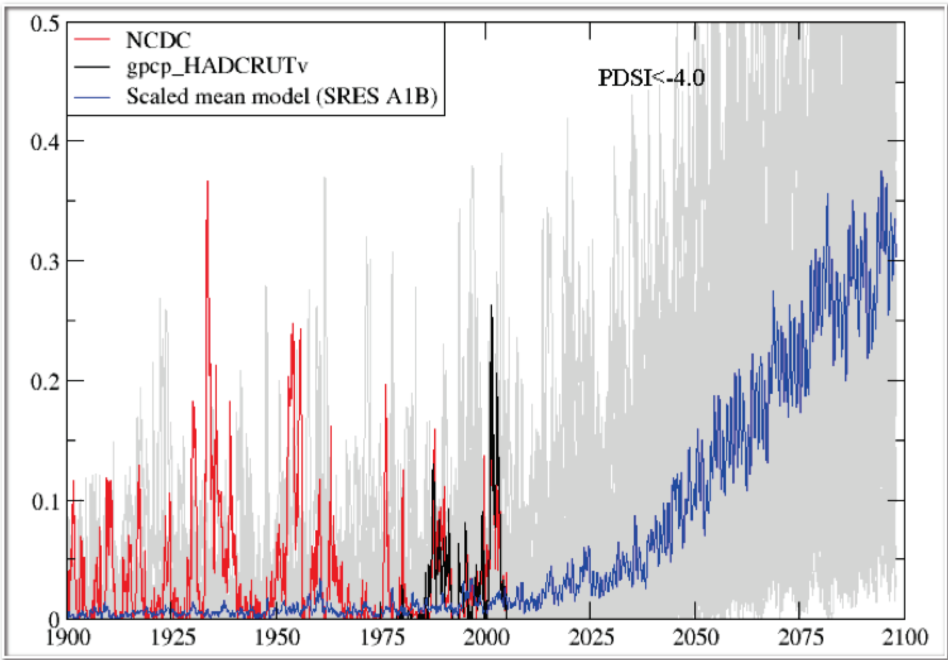

Figure 2.21: Extreme Drought in the U.S. and Mexico, Past and Future

Caption: The percentage area of the U.S. and Mexico in extreme drought according to projections of the Palmer Drought Severity Index under a mid-range emissions scenario (SRES A1B). The Palmer Drought Severity Index is the most widely used measure of drought, although it is more sensitive to temperature than other drought indices and may over-estimate the magnitude of drought increases. The red line is based on observed temperature and precipitation. The blue line is from the average of 19 different climate models. The gray lines in the background are individual results from over 70 different simulations from these models. These results suggest an increasing probability of drought over this century throughout most of the U.S. Source: (Wehner et al. 2011)

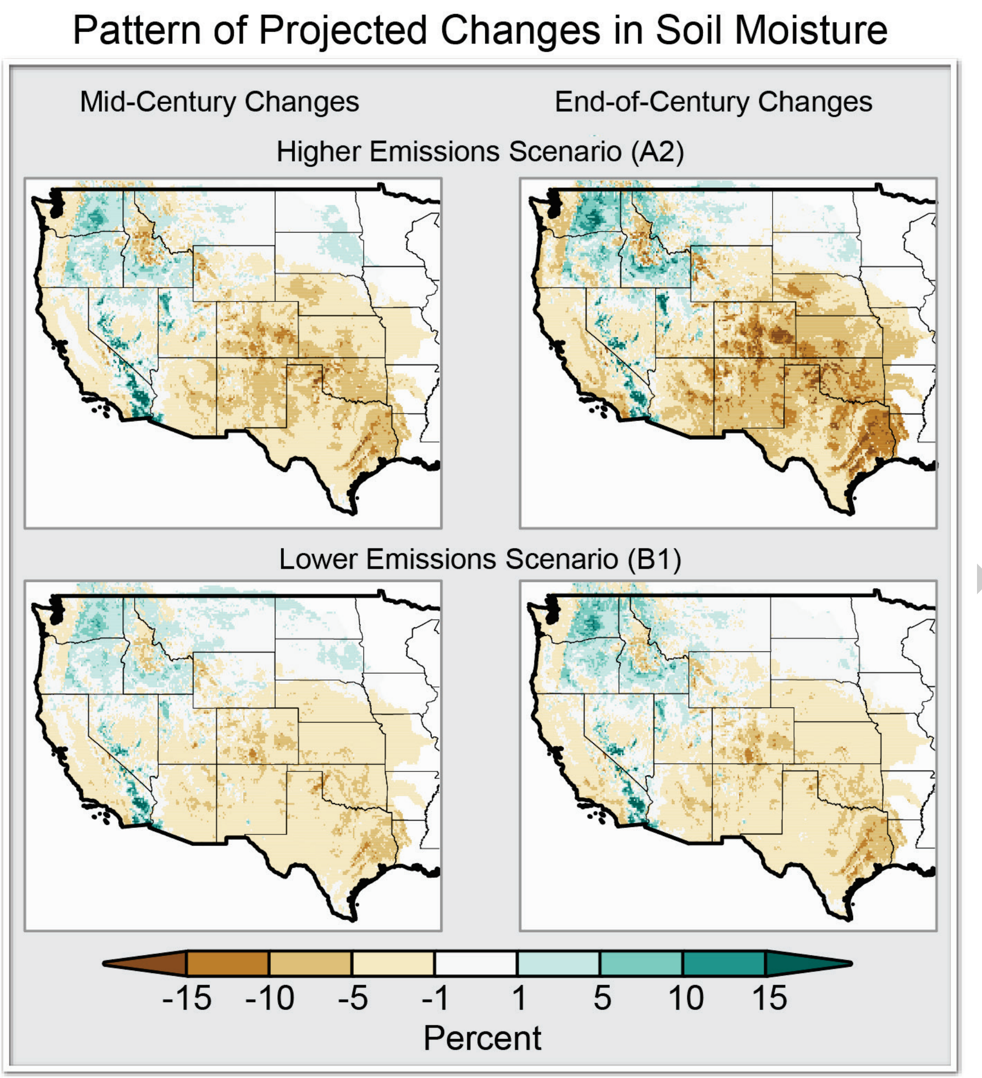

Figure 2.22: Pattern of Projected Changes in Soil Moisture

Caption: Average percent change in soil moisture compared to 1971-2000, as projected in the middle of this century (2041-2070) and late this century (2071-2100) under two emissions scenarios, a lower scenario assuming significant reductions in emissions (B1) and a higher scenario (A2) assuming that emissions continue to grow (Dai 2012; Liang et al. 1996; Liang et al. 1994; Maurer et al. 2002; Nijssen et al. 1997; Wood and Lettenmaier 2006; Wood et al. 2005). The future drying of soils in most areas simulated by this sophisticated hydrologic model (VIC model) is consistent with the future drought increases using the simpler Palmer Drought Severity Index (PDSI) metric. (Figure source: NOAA NCDC / CICS-NC. Data from VIC model.)

Changes in Storms

There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm. With regard to other types of storms that affect the U.S., winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the U.S. Other trends in severe storms, including the numbers of hurricanes and the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds are uncertain and are being studied intensively.

Trends in the occurrences of storms, ranging from severe thunderstorms to winter storms to hurricanes, are subject to much greater uncertainties than trends in temperature and variables that are directly related to temperature (snow and ice cover, ocean heat content, sea level). Recognizing that the impacts of changes in the frequency and intensity of these storms can easily exceed the impacts of changes in average temperature or precipitation, climate scientists are actively researching the connections between climate change and severe storms.

Hurricanes

There has been a substantial increase in virtually every measure of hurricane activity in the Atlantic since the 1970s. These increases are linked, in part, to higher sea surface temperatures in the region that Atlantic hurricanes form in and move through. Numerous factors influence these local sea surface temperatures, including human-induced emissions of heat-trapping gases and particulate pollution and natural variability (Booth et al. 2012; Camargo et al. 2012; Evan et al. 2012; Evan et al. 2011; Evan et al. 2009; Mann and Emanuel 2006; Ting et al. 2009; Zhang and Delworth 2009). However, hurricanes respond to more than just sea surface temperature. How hurricanes respond also depends on how the local atmosphere responds to changes in local sea surface temperatures, and this atmospheric response depends critically on the *cause* of the change (Emmanuel 2012; Zhang and Delworth 2009);. For example, the atmosphere responds differently when local sea surface temperatures increase due to a local decrease of particulate pollution that allows more sunlight through to warm the ocean, versus when sea surface temperatures increase more uniformly around the world due to increased amounts of heat-trapping gases. So the link between hurricanes and ocean temperatures is complex and this is an active area of research. Climate models that incorporate the best understanding of all these factors project further increases in the frequency and intensity of the strongest Atlantic hurricanes, as well as increased rainfall rates in response to continued warming of the tropical oceans by heat-trapping gases. Hurricane activity in other ocean basins has not shown such clear increases as those found in the Atlantic. Consequently, there is much greater uncertainty that hurricane activity in those basins has increased substantially in the past 40 years or so. Reducing these uncertainties is another active area of research.

Severe Convective Storms

Tornadoes and other severe thunderstorm phenomena frequently cause as much annual property damage in the U.S. as do hurricanes, and often cause more deaths. Although recent research has yielded insights into the connections between global warming and the factors that cause tornados and severe thunderstorms (such as atmospheric instability and increases in wind speed with altitude (Del Genio et al. 2007; Trapp et al. 2007)), these relationships remain mostly unexplored, largely because of the challenges in observing thunderstorms and tornadoes and simulating them with computer models.

Winter Storms

Over the U.S., changes in winter storm frequency and intensity are small and not significant, with the exception that there is limited evidence of an overall increase in storm activity near the northeast and northwest U.S. coastlines during the second half of the 1950-2010 period (Vose, 2012). However, for the Northern Hemisphere as a whole, there is evidence of an increase in both storm frequency and intensity during the cold season since 1950 (Vose, 2012), with storm tracks having shifted slightly towards the poles (Wang et al. 2006; Wang et al. 2012). Extremely heavy snowstorms increased in number during the last century in northern and eastern parts of the U.S., but have been less frequent since 2000 (Kunkel et al. 2012h; Squires et al. 2009). Total seasonal snowfall has generally decreased in southern and some western areas (Kunkel et al. 2009b), increased in the northern Plains and Great Lakes (Kunkel et al. 2009a, 2009b), and not changed in other areas, such as the Sierra Nevada (Christy 2012). Very snowy winters have generally been decreasing in frequency in most regions over the last 10 to 20 years, although the Northeast has been seeing a normal number of such winters (Kunkel et al. 2009). Heavier-than-normal snowfalls recently observed in the Midwest and Northeast U.S. in some years, with little snow in other years, are consistent with indications of increased blocking of the wintertime circulation of the Northern Hemisphere (Francis and Vavrus 2012). Overall snow cover has decreased in the Northern Hemisphere, due in part to higher temperatures that shorten the time snow spends on the ground (BAMS 2012).

Observed Trends in Hurricane Intensity

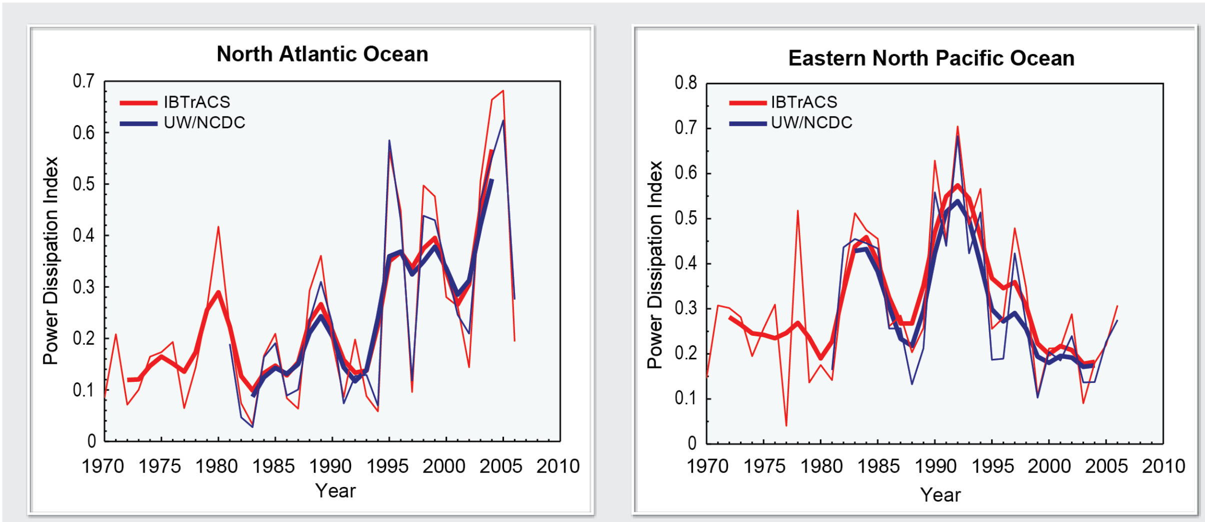

Figure 2.23: Observed Trends in Hurricane Intensity

Caption: Recent variations of the Power Dissipation Index (PDI), a measure of overall hurricane intensity in a hurricane season. Historical and satellite observations show a significant upward trend in the strength of hurricanes and in the number of strong hurricanes (Category 4 and 5) in the North Atlantic from 1983 to 2009. A significant decreasing trend in hurricane intensity is detected for the eastern North Pacific from 1984 to 2009, but no trend in the number of storms is apparent. Updated from (Kossin et al. 2007)

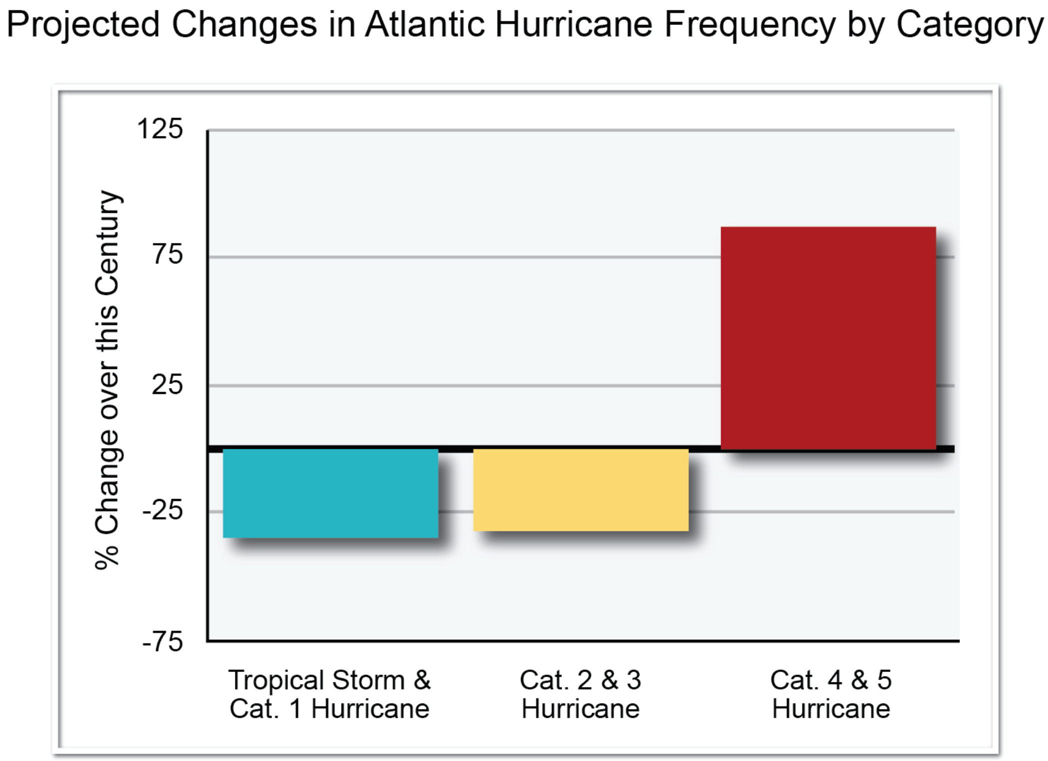

Figure 2.24: Projected Changes in Atlantic Hurricane Frequency by Category

Caption: Model projections of percentage changes in Atlantic hurricane and tropical storm frequencies for different storm categories, by the late this century. Projected changes are for the period 2081-2100 compared with the period 2001-2020. (Figure source: NOAA GFDL)

Sea Level Rise

Global sea level has risen by about 8 inches since 1880. It is projected to rise another 1 to 4 feet by 2100.

The oceans are absorbing over 90% of the increased atmospheric heat associated with emissions from human activity (Church et al. 2011). Like mercury in a thermometer, water expands as it warms up (this is referred to as "thermal expansion") causing sea levels to rise. Melting of glaciers and ice sheets is also contributing to sea level rise at increasing rates (Arctic Monitoring and Assessment Programme 2011).

Since the late 1800s, tide gauges throughout the world have shown that global sea level has risen by about 8 inches. Proxy data have shown that this rate of sea level rise is faster than at any time in at least the past 2000 years (Kemp et al. 2012). Since 1992, the rate of global sea level rise measured by satellites has been roughly twice the rate observed over the last century, providing evidence that the current rate is faster still (Church and White 2011a).

Projecting future rates of sea level rise is challenging. Even the most sophisticated climate models, which explicitly represent Earth's physical processes, cannot simulate recent rapid changes in ice sheet dynamics, and thus tend to underestimate sea level rise. In recent years, "semi-empirical" models, based on statistical relationships between historical rates of global warming and sea level rise, have been developed. Early efforts at semi-empirical models suggested much higher rates of sea level rise (as much as 6 feet by 2100) (Jevrejeva et al. 2010; Vermeer and Rahmstorf 2009). More recent semi-empirical models have suggested upper ends closer to 3 or 4 feet by 2100 (Jevrejeva et al. 2012; Rahmstorf et al. 2012). It is not clear, however, whether these statistical relationships will hold in the future.

Scientists are working to narrow the range of sea level rise projections for this century. Recent projections show that for even the lowest emissions scenarios, thermal expansion of ocean waters (Yin 2012) and the melting of small mountain glaciers (Marzeion et al. 2012) will result in 11 inches of sea level rise by 2100, even without any contribution from the ice sheets in Greenland and Antarctica. This suggests that about 1 foot of global sea level rise by 2100 is probably a realistic low end. On the high end, recent work suggests that 4 feet is plausible. (Gladstone et al. 2012; Jevrejeva et al. 2012; Joughin et al. 2010; Katsman et al. 2011; Rahmstorf et al. 2012). In the context of risk-based analysis, some decision makers may wish to use a wider range of scenarios, from 8 inches to 6.6 feet by 2100 (Burkett and Davidson 2012; Parris et al. 2012). In particular, the high end of these scenarios may be useful for decision makers with a low tolerance for risk (Burkett and Davidson 2012; Parris et al. 2012) (see figure on global sea level rise). Although scientists cannot yet assign likelihood to any particular scenario, in general, higher emissions scenarios that lead to more warming would be expected to lead to higher amounts of sea level rise.

Nearly 5 million people in the U.S. live within 4 feet of the local high-tide level. In the next several decades, storm surges and high tides could combine with sea level rise and land subsidence to further increase flooding in many of these regions (Strauss et al.

2012). Sea level rise is not expected to stop in 2100. The oceans take a very long time to respond to warmer conditions at the Earth's surface. Ocean waters will therefore continue to warm and sea level will continue to rise for many centuries.

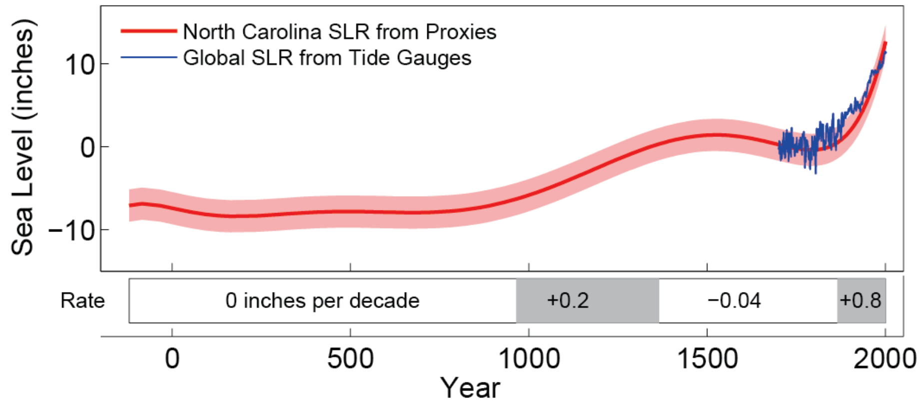

Figure 2.25

Caption: Rates of sea level change in the North Atlantic Ocean based on data collected from the U.S. East Coast (Kemp et al. 2012) (red line, pink band shows the uncertainty range) compared with a reconstruction of global sea level rise based on tide gauge data (Jevrejeva et al. 2008) (blue line). (Figure source: Josh Willis, NASA Jet Propulsion Laboratory)

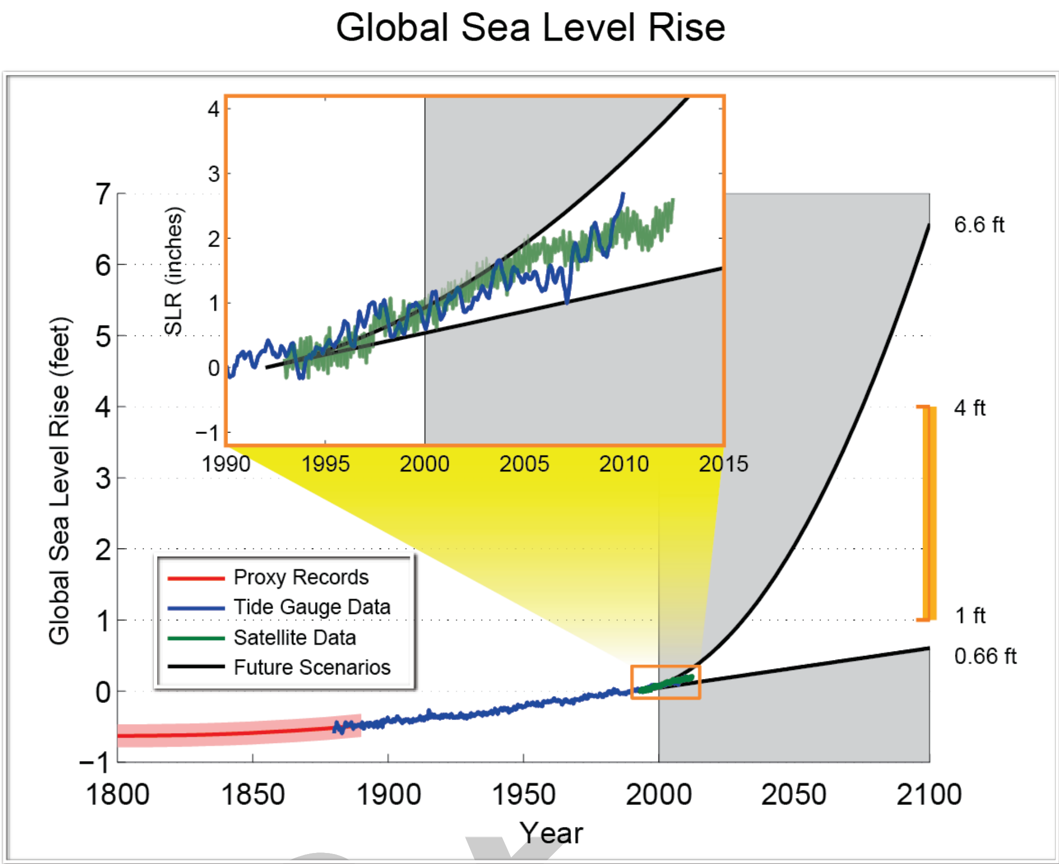

Figure 2.26: Global Sea Level Rise

Caption: Estimated, observed and possible amounts of global sea level rise from 1800 to 2100. Proxy estimates (Kemp et al. 2012) (for example, based on sediment records) are shown in red (pink band shows uncertainty), tide gauge data in blue (Church and White 2011a), and satellite observations are shown in green (Nerem et al. 2010). The future scenarios range from 0.66 feet to 6.6 feet in 2100 (Parris et al. 2012). Higher or lower amounts of sea level rise are considered implausible, as represented by the gray shading. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100, which falls within the larger risk-based scenario range. The large projected range reflects uncertainty about how glaciers and ice sheets will react to the warming ocean, the warming atmosphere, and changing winds and currents. As seen in the observations, there are year-to-year variations in the trend. (Figure source: Josh Willis, NASA Jet Propulsion Laboratory)

Melting Ice

Rising temperatures are reducing ice on land, lakes, and sea. This loss of ice is expected to continue.

Rising temperatures across the U.S. have reduced lake ice, sea ice, glaciers, and seasonal snow cover over the last few decades (Arctic Monitoring and Assessment Programme 2011). In the Great Lakes, for example, total winter ice coverage has decreased by 63% since the early 1970s (Wang et al. 2011).

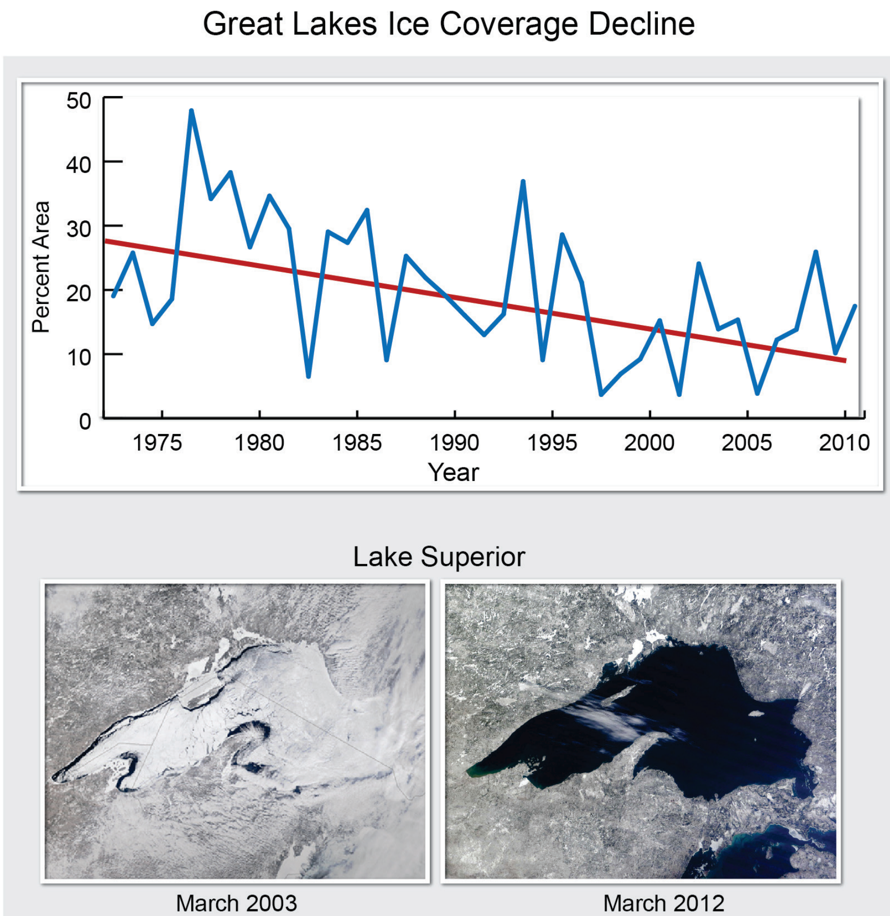

Figure 2.27: Great Lakes Ice Coverage Decline

Caption: Blue line shows annual average Great Lakes ice coverage from 1973 to 2011 and red line shows the trend. (Figure source updated from Wang et al. 2011) Satellite images show Lake Superior in a high ice year and a more recent low ice year. (Satellite images courtesy of NASA)

Sea ice in the Arctic has also decreased dramatically since the late 1970s, particularly in summer and autumn. Since the satellite record began in 1978, minimum Arctic sea ice extent (which occurs in early to mid September) has decreased by more than 40% (NSIDC 2012). This decline is unprecedented in the historical record and is consistent with human-induced climate change. The 2012 sea ice minimum broke the preceding record (set in 2007) by more than 200,000 square miles. Ice loss increases Arctic warming by replacing white, reflective ice with dark water that absorbs more energy from the sun. More open water can also increase snowfall over northern land areas and increase the north-south meanders of the jet stream, consistent with the occurrence of unusually cold and snowy winters at mid-latitudes in several recent years (Francis and Vavrus 2012; Liu et al. 2012).

Arctic Sea Ice Decline

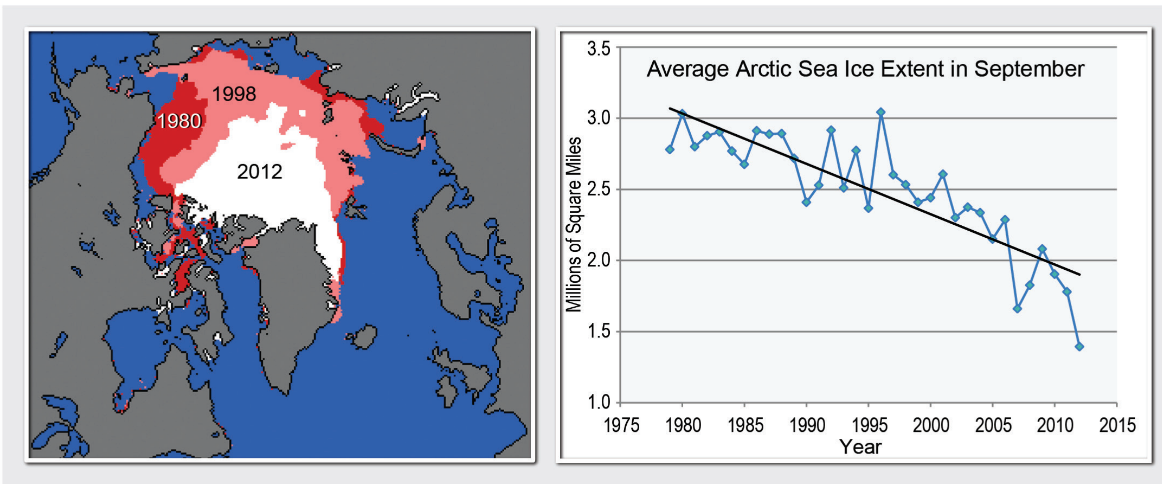

Figure 2.28: Arctic Sea Ice Decline

Caption: Summer Arctic sea ice has declined dramatically since satellites began measuring it in 1979. The extent of sea ice in September 2012, shown in white in the figure on the left, was more than 40% below the median for 1979-2000. It is also notable that the ice has become much thinner in recent years, so its total volume has declined even more rapidly than the extent shown here (Arctic Monitoring and Assessment Programme 2011). The graph on the right shows annual variations in September Arctic sea ice extent for 1979-2012. (Figure and data from National Snow and Ice Data Center)

The loss of sea ice has been greater in summer than in winter. The Bering Sea, for example, experiences sea ice only in the winter-spring portion of the year, and shows no trend in ice coverage over the past 30 years. However, seasonal ice in the Bering Sea and elsewhere in the Arctic is thin and susceptible to rapid melt during the following summer. Sea ice in the Antarctic is largely seasonal and has shown a slight increase in extent since 1979.

This seasonal pattern of observed ice loss is generally consistent with simulations by global climate models, in which the extent of sea ice decreases more rapidly in summer than in winter. However, the models tend to underestimate the amount of decrease since 2007. Projections by these models indicate that summer sea ice in the Arctic Ocean could disappear before mid-century under scenarios that assume continued growth in global emissions, although sea ice would still form in winter (Stroeve et al. 2012; Wang and Overland 2009). Even during a long-term decrease, occasional temporary increases in Arctic summer ice can be expected over timescales of a decade or so because of internal variability (Kay et al. 2011).

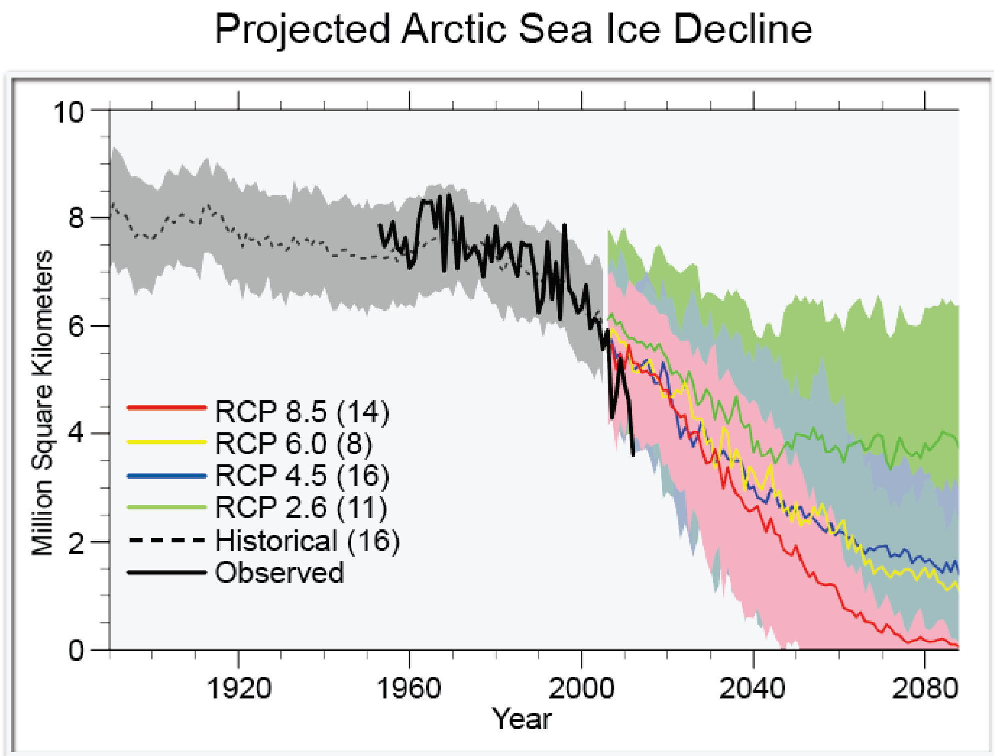

Figure 2.29: Projected Arctic Sea Ice Decline

Caption: Model simulations of Arctic sea ice extent for September, 1900-2100, based on observed concentrations of heat-trapping gases and particles (through 2005) and four emissions scenarios: RCP 2.6 (green line), RCP 4.5 (blue line), RCP 6.0 (yellow line), and RCP 8.5 (red line); numbers in parentheses denote number of models represented. Colored lines for RCP scenarios are model averages (CMIP5). Shading shows ranges among models (pink for RCP 8.5 simulations, blue for RCP 4.5 simulations). The thick black line shows observed data for 1953-2012. These newer model simulations project acceleration in sea ice loss relative to older simulations. (Figure source: adapted from Stroeve et al. 2012).

The surface of the Greenland Ice Sheet has been experiencing summer melting over increasingly large areas during the past several decades. In the decade of the 2000s, the daily melt area summed over the warm season was double the corresponding amounts of the 1970s (Fettweis et al. 2011), culminating in summer melt that was far greater (97% of the Greenland Ice Sheet area) in 2012 than in any year since the satellite record began in

1979. More importantly, the rate of mass loss from the Greenland Ice Sheet has accelerated in recent decades, increasing Greenland's contribution to sea level rise (Dahl-Jensen et al. 2011). The proportion of global sea level rise coming from Greenland is expected to continue to increase (Dahl-Jensen et al. 2011). However, the dynamics of the Greenland Ice Sheet are generally not included in present global climate models.

Glaciers are retreating and/or thinning in Alaska and in the lower 48 states. In addition, permafrost temperatures are increasing over Alaska and much of the Arctic. Regions of discontinuous permafrost in interior Alaska (where annual average soil temperatures are already close to 32°F) are highly vulnerable to thaw. Thawing permafrost releases carbon dioxide and methane, heat-trapping gases that contribute to even more warming. Methane emissions have been detected from Alaskan lakes underlain by permafrost (Walter et al. 2007), and measurements suggest potentially even greater releases from the Arctic continental shelf in the East Siberian Sea (Shakhova et al. 2010).

Ocean Acidification

The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about potential impacts on marine ecosystems.

As human-induced emissions of carbon dioxide (CO_2) build up in the atmosphere, excess CO_2 is dissolving into the oceans where it reacts with seawater to form carbonic acid, lowering ocean pH levels ("acidification") and threatening a number of marine ecosystems (Doney et al. 2009). Currently, the oceans absorbs about a quarter of the CO_2 humans produce every year (Le Quere et al. 2009). Over the last 250 years, the oceans have absorbed 530 billion tons of CO_2, increasing the acidity of surface waters by 30% (Caldeira and Wickett 2003; Hall-Spencer et al. 2008; Hönisch et al. 2012). Although the average oceanic pH can vary on interglacial timescales (Caldeira and Wickett 2003), the current observed rate of change is roughly 50 times faster than known historical change (Byrne et al. 2010). Regional factors such as coastal upwelling (Feely et al. 2008), changes in riverine and glacial discharge rates (Mathis et al. 2011), sea ice loss (Yamamoto-Kawai et al. 2009), and urbanization (Feely et al. 2010) have created "ocean acidification hotspots" where changes are occurring at even faster rates.

The acidification of the oceans has already caused a suppression of carbonate mineral concentrations that are critical for marine calcifying animals such as corals, zooplankton, and shellfish. Many of these animals form the foundation of the marine food web. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Ocean acidification puts this important resource at risk.

Observations have shown that the northeastern Pacific Ocean, including the arctic and sub-arctic seas, is particularly susceptible to significant shifts in pH and calcium carbonate concentrations. Recent analyses show that large areas of the oceans along the U.S. west coast (Gruber et al. 2012), the Bering Sea, and the western Arctic Ocean (Orr et al. 2005) will become difficult for calcifying animals within the next 50 years. In particular, animals that form calcium carbonate shells, including corals, crabs, clams, oysters, and tiny free-swimming snails called pteropods, could be particularly vulnerable, especially during the larval stage (Doney et al. 2012; Fabry et al. 2009).

Projections indicate that in a high emissions scenario such as SRES A2 or RCP 8.5, current pH could be reduced from the current level of 8.07 to as low as 7.67 by the end of the century, roughly five times the amount of acidification that has already occurred (NOAA 2012). Such large changes in ocean pH have probably not been experienced on the planet for the past 21 million years, and scientists are unsure whether and how quickly ocean life could adapt to such rapid acidification.

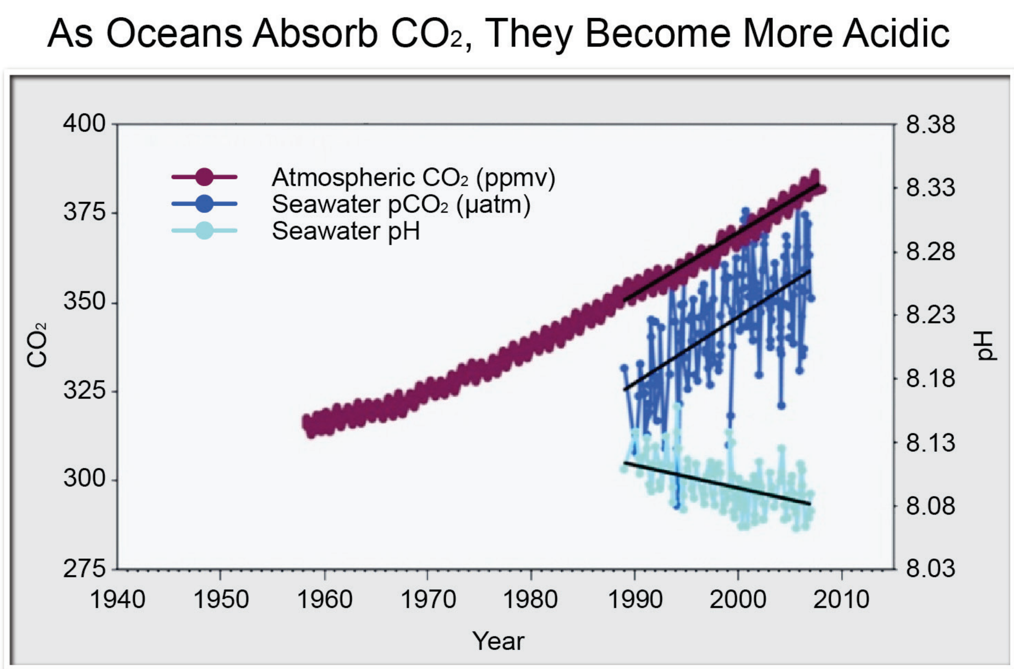

Figure 2.30: As Oceans Absorb CO_2, They Become More Acidic

Caption: The correlation between rising levels of carbon dioxide in the atmosphere at Mauna Loa with rising carbon dioxide levels and falling pH in the nearby ocean at Station Aloha. As carbon dioxide accumulates in the ocean, the water becomes more acidic. Figure source: modified from (Feel.y et al. 2008).

Shells Dissolve in Acidified Ocean Water

Figure 2.31: Shells Dissolve in Acidified Ocean Water

Caption: The Pteropod, or "sea butterfly", is a tiny sea creature about the size of a small pea. Pteropods are eaten by marine species ranging in size from krill to whales and are a major source of food for North Pacific young salmon. The photos above show what happens to a pteropod's shell when placed in seawater with pH and carbonate levels projected for the year 2100. The shell slowly dissolves after 45 days. (Photo credit: National Geographic Images)

Traceable Accounts

Chapter 2: Our Changing Climate

Key Message Process: Development of the key messages involved: 1) discussions of the lead authors and accompanying analyses conducted via one in-person meeting plus a number of teleconferences over the last 8 months (from February thru September 2012) including reviews of the scientific literature; and 2) the findings from four special workshops that related to the latest science understanding of climate extremes. Each workshop had a different theme related to climate extremes, had approximately 30 attendees (the CMIP5 meeting had more than 100), and resulted in a paper submitted to BAMS (2012). The first was held in July 2011, titled Monitoring Changes in Extreme Storm Statistics: State of Knowledge (https://sites.google.com/a/noaa.gov/severe-storms-workshop/). The second was held in November 2011, titled November 2011 – Forum on Trends and Causes of Observed Changes in Heatwaves, Coldwaves, Floods, and Drought (https://sites.google.com/a/noaa.gov/heatwaves-coldwaves-floods-droughts/). The third was held in January 2012, titled Forum on Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts (https://sites.google.com/a/noaa.gov/extreme-winds-waves-extratropical-storms/). The fourth, the CMIP5 results workshop, was held in March 2012 in Hawaii.

In developing key messages, the Chapter Author Team engaged in multiple technical discussions over the last 8 months via teleconferences and emails as they reviewed over 80 technical inputs provided by the public, as well as other published literature, and professional judgment. These discussions were supported by targeted consultation with additional experts, and they were based on criteria that help define "key vulnerabilities." A consensus-based approach was used for final key message selection.

Key message #1/11	**Global climate is changing now and this change is apparent across a wide range of observations. The climate change of the past 50 years is primarily due to human activities.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Generally, those reports did not add much to the author team's process in the way of observation and model data analyses and their use of the peer-reviewed literature. Evidence for changes in global climate arises from multiple analyses of data from in-situ, satellite, and other records undertaken by many groups over several decades (Kennedy et al. 2010). Changes in the mean state have been accompanied by changes in the frequency and nature of extreme events (Alexander et al. 2006) . A substantial body of analysis comparing the observed changes to a broad range of climate simulations consistently points to the necessity of invoking human-caused changes to adequately explain the observed climate system behavior(Gillett et al. 2012; Stott et al. 2010). The influence of human impacts on the climate system was also observed in a number of individual climate variables (AchutaRao et al. 2006; Gillett and Stott 2009; Min et al. 2011; Pall et al. 2011; Santer et al. 2007; Santer 2012; Willett et al. 2007) .
New information and remaining uncertainties	Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional, scales, and especially for extreme events and our ability to simulate and attribute such changes using climate models. Innovative new approaches to climate data analysis, continued improvements in climate modeling, and instigation and maintenance of reference quality observation networks such as the US Climate Reference Network can all reduce uncertainties.
Assessment of confidence based	There is **very high** confidence that global climate is changing and this change is apparent across a wide range of observations given the evidence base and remaining

on evidence	uncertainties. All observational evidence is consistent with a warming climate since the late 1800's. There is **very high** confidence that the climate change of the past 50 years is primarily due to human activities given the evidence base and remaining uncertainties. Recent changes have been consistently attributed in large part to human factors across a very broad range of climate system characteristics.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #2/11	**Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the climate is to those emissions.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Evidence of continued global warming is based on past observations of climate change and our knowledge of the climate system's response to heat-trapping gases. Models have projected increased temperature under a number of different scenarios (IPCC 2007; Schnellnhuber et al. 2006; Taylor et al. 2012). Evidence that the planet has warmed is "unequivocal" (IPCC 2007) , and is corroborated though multiple lines of evidence, as is the conclusion that the causes are very likely human in origin. The evidence for future warming is based on fundamental understanding of the behavior of heat-trapping gases in the atmosphere. Model simulations provide bounds on the estimates of this warming.
New information and remaining uncertainties	There are several major sources of uncertainty in making projections of climate change. The relative importance of these changes over time. In next few decades, the effects of natural variability will be an important source of uncertainty for climate change projections. Uncertainty in future human emissions becomes the largest source of uncertainty by the end of this century. Uncertainty in how sensitive the climate is to increased concentrations of heat-trapping gases is especially important beyond the next few decades. Uncertainty in natural climate drivers, e.g. how much will the solar output change over this century, also affects the accuracy of projections.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **very high** that global climate is projected to continue to change over this century and beyond**.**

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #3/11	**U.S. average temperature has increased by about 1.5 degrees F since record keeping began in 1895; more than 80% of this increase has occurred since 1980. The most recent decade was the nation's warmest on record. U.S. temperatures are expected to continue to rise. Because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, smooth across the country or over time.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Evidence for the long-term increase in temperature is based on analysis of daily maximum and minimum temperature observations from the U.S. Cooperative Observer Network. With the increasing understanding of U.S. temperature measurements, (Fall et al. 2010; Fall et al. 2011; Karl et al. 1986; Menne and Williams Jr 2009; Menne et al. 2009; Menne et al. 2010; Vose et al. 2012; Williams et al. 2012) a temperature increase has been observed and is projected to continue rising (Menne et al. 2009). Observations show that the last decade was the warmest in over a century. A number of climate model simulations were performed to assess past, and to forecast future changes in climate; temperatures are generally projected to increase across the U.S. All peer-reviewed studies to date satisfying the assessment process agree that the U.S. has warmed over the past century and in the past several decades. Climate model simulations consistently project future warming and bracket the range of plausible increases.
New information and remaining uncertainties	There have been substantial advances in our understanding of the U.S. temperature record since the previous National Climate Assessment (Fall et al. 2010; Fall et al. 2011; Karl et al. 2009; Menne and Williams Jr 2009; Menne et al. 2009; Menne et al. 2010; Vose et al. 2012; Williams et al. 2012). A potential uncertainty is the sensitivity of temperature trends to bias adjustments that account for historical changes in station location, temperature instrumentation, observing practice, and siting conditions. However, quality analyses of these uncertainties have not found any major issues of concern affecting the conclusions made in the key message While numerous studies verify the efficacy of the bias adjustments, the information base can be improved in the future through continued refinements to the adjustment approach. Model biases are subject to changes in physical effects on climate; for example, model biases can be affected by snow cover and hence are subject to change in a warming climate.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **very high** that because human-induced warming is superimposed on a naturally varying climate, the temperature rise has not been, and will not be, smooth across the country or over time.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #4/11	**The length of the frost-free season (and the corresponding growing season) is increasing nationally, with the largest increases occurring in the western U.S., affecting ecosystems and agriculture. Continued lengthening of the growing seasons across the U.S. is projected.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Evidence that the length of the frost-free season is lengthening is based on extensive analysis of daily minimum temperature observations from the U.S. Cooperative Observer Network. The geographic variations of increasing number of frost-free days are similar to changes in mean temperature. Separate analysis of surface data also indicates a trend towards an earlier onset of spring. Key references: U.S. Environmental Protection Agency (2010), Dragoni et al. (2011), Jeong et al.(2011), Ziska et al.(2011). Nearly all studies to date published in the peer-reviewed literature (e.g., Dragoni et al. (2011), U.S. Environmental Protection Agency (2010), Jeong et al.(2011)) agree that the freeze-free and growing seasons have lengthened. This is most apparent in the western U.S. Peer-reviewed studies also indicate that continued lengthening will occur if concentrations of heat-trapping gases continue to rise. The magnitude of future changes based on model simulations is large in the context of historical variations.
New information and remaining uncertainties	A key issue (uncertainty) is the potential effect of station inhomogeneities on observed trends, particularly those arising from instrumentation changes. A second key issue is the extent to which observed regional variations (more lengthening in the west/less in the east) will persist into the future. Local temperature biases in climate models contribute to the uncertainty in projections. Viable avenues to improving the information base are to investigate the sensitivity of observed trends to potential biases introduced by station inhomogeneities and to investigate the causes of observed regional variations.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **very high** that the length of the frost-free season (also referred to as the growing season) is increasing nationally, with the largest increases occurring in the western U.S, affecting ecosystems, gardening, and agriculture. Confidence is **very high** that there will be continued lengthening of these seasons across the U.S. given the evidence base.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #5/11	**Precipitation over the U.S. has increased on average during the period since 1900, with the largest increases the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Evidence of long-term change in precipitation is based on analysis of daily observations from the U.S. Cooperative Observer Network. Published work shows the regional differences in precipitation (McRoberts and Nielsen-Gammon 2011; Peterson et al. 2012) . Evidence of future change is based on our knowledge of the climate system's response to heat-trapping gases and an understanding of the regional mechanisms behind the projected changes (e.g., IPCC 2007).
New information and remaining uncertainties	A key issue (uncertainty) is the sensitivity of observed precipitation trends to historical changes in station location, rain gauges, and observing practice. A second key issue is the extent to which observed regional variations will persist into the future. An uncertainty in projected precipitation concerns the extent of the drying of the Southwest. Shifts in precipitation patterns due to changes in pollution are uncertain and is an active research topic. Viable avenues to improving the information base are to investigate the sensitivity of observed trends to potential biases introduced by station changes and to investigate the causes of observed regional variations. A number of peer-reviewed studies (e.g., (McRoberts and Nielsen-Gammon 2011; Peterson et al. 2012)) document precipitation increases at the national scale as well as regional-scale increases and decreases. The variation in magnitude and pattern of future changes from climate model simulations is large relative to observed (and modeled) historical variations.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **high** that precipitation over the U.S. has increased on average during the period since 1900, with the largest increases the Midwest, southern Great Plains, and Northeast. Confidence is **high** given the evidence base and uncertainties that portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced precipitation decreases. There **is less certainty** for Southwest mountain states because they sit in the transition region. Confidence is **high** given the evidence base and uncertainties that more winter and spring precipitation is projected for the northern U.S., and less for the Southwest, over this century.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See KM#1.

Key message #6/11	**Heavy downpours are increasing nationally, especially over the last three to five decades. Largest increases are in the Midwest and Northeast. Further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Evidence that extreme precipitation is increasing is based primarily on analysis of hourly and daily precipitation observations from the U.S. Cooperative Observer Network and is supported by observed increases in atmospheric water vapor (Dai 2012). Recent publications have projected an increase in extreme precipitation events (Kunkel et al. 2012h; Wang and Overland 2009), with some areas getting larger increases (Karl et al. 2009) and some getting decreases (Wehner 2012; Wuebbles et al. 2012). Nearly all studies to date published in the peer-reviewed literature agree that extreme precipitation event number and intensity have risen, when averaged over the United States. The pattern of change for the wettest day of the year is projected to roughly follow that of the average precipitation with both increases and decreases across the U.S. Extreme hydrologic events are likely to increase over most of the U.S.
New information and remaining uncertainties	A key issue (uncertainty) is the ability of climate models to simulate precipitation. This is one of the more challenging aspects of modeling of the climate system because precipitation involves not only large-scale processes that are well-resolved by models but small-scale process, such as convection, that must be parameterized in the current generation of global and regional climate models. Viable avenues to improving the information base are to perform some long very high resolution simulations of this century's climate under different emissions scenarios
Assessment of confidence based on evidence	Given the evidence base and uncertainties, confidence is **high** that heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast. Confidence is **high** that further increases in the frequency and intensity of extreme precipitation events are projected for most U.S. areas given the evidence base and uncertainties.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See KM#1.

Key message #7/11	**Certain types of extreme weather events have become more frequent and intense, including heat waves, floods, and droughts in some regions. The increased intensity of heat waves has been most prevalent in the western parts of the country, while the intensity of flooding events has been more prevalent over the eastern parts. Droughts in the Southwest and heat waves everywhere are projected to become more intense in the future.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Analysis of U.S. temperature records indicates that record cold events are becoming progressively less frequent relative to record high events. Evidence for these trends in the United States is provided by Meehl et al.(2009). Cited papers by Stott et al. (2010) and Christidis et al.(2011) contain evidence for the corresponding trends in a global framework. A number of publications have explored the increasing trend of heat waves (Karl et al. 2008; Stott et al. 2010; Trenberth 2011). Additionally, heat waves observed in the southern Great Plains (Karl et al. 2009), Europe (Stott et al. 2010; Trenberth 2011) and Russia (Christidis et al. 2011; Duffy and Tebaldi 2012; Meehl et al. 2009) have now been shown to have a higher probability of having occurred because of human-induced climate change. Some parts of the U.S. have been seeing changing trends for floods and droughts over the last 50 years, with some evidence for human influence (Barnett et al. 2008; Hidalgo et al. 2009; Pall et al. 2011; Peterson et al. 2012; Pierce et al. 2008). Further evidence for these trends is provided by Trenberth (2011). Projections of increased drought are supported by the results of Wehner et al.(2011), with a number of publications projecting drought as becoming a more normal condition over much of the southern and central U.S. (most recent references: Dai 2012; Hoerling et al. 2012b). Analyses of U.S. daily temperature records indicate that low records are being broken at a much smaller rate than high records, and at the smallest rate in the historical record. However, in certain localized regions, natural variations can be as large or larger than the human induced change.
New information and remaining uncertainties	The key uncertainty regarding projections of future drought is how soil moisture responds to precipitation changes and potential evaporation increases. Most studies indicate that many parts of the U.S. will experience drier soil conditions but the amount of that drying is uncertain. Natural variability is also an uncertainty affecting extreme event occurrences in shorter timescales (several years to decades), but the changes become larger relative to natural variability as the timescale lengthens. Stakeholders should view the occurrence of extreme events in the context of increasing probabilities. Continuation of long term temperature and precipitation observations is critical to monitoring trends in extreme weather events.
Assessment of confidence based on evidence	Give the evidence base and uncertainties: Heat waves have become more frequent and intense, and confidence is **high** that these trends are projected to continue. Droughts have become more frequent and intense in some regions, and confidence is **high** that these trends are projected to continue.

	Floods have become more frequent and intense in some regions, and confidence is **medium** to **high** that these trends are projected to continue.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #8/11	**There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm. With regard to other types of storms that affect the U.S., winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the U.S. Other trends in severe storms, including the numbers of hurricanes and the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds are uncertain and are being studied intensively.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Recent studies suggest that the most intense Atlantic hurricanes have become stronger since the early 1980s, as documented by (Kossin et al. 2007) . While this is still the subject of active research, this trend is projected to continue (Bender et al. 2010). Current work by Vose et al. (2012) has provided evidence in the increase in frequency and intensity of winter storms, with the storm tracks shifting poleward (Wang et al. 2006; Wang et al. 2012), but some areas have experienced a decrease in winter storm frequency (Karl et al. 2009). Some recent research has provided insight into the connection of global warming to tornados and severe thunderstorms (Del Genio et al. 2007; Trapp et al. 2007).
New information and remaining uncertainties	Detecting trends in Atlantic and eastern North Pacific hurricane activity is challenged by a lack of consistent historical data and limited understanding of all of the complex interactions between the atmosphere and ocean that influence hurricanes. Significant uncertainties remain in making projections of hurricane number and intensity. While the best analyses to date suggest an increase in intensity and in the number of most intense storms over the century, there remain significant uncertainties. The figure in the chapter for KM#8 that shows projected changes in occurrences of hurricanes of different intensities includes data points from different models, illustrating the spread. Other types of storms have even greater uncertainties in their recent trends and projections. The text for this key message explicitly acknowledges the state of knowledge, pointing out "what we don't know".
Assessment of confidence based on evidence	Given the evidence and uncertainties, confidence is **medium** that the strongest hurricanes are projected to increase in intensity as the oceans warm due to more available energy. Confidence is **low** regarding other trends in severe storms due to the many uncertainties that remain about frequency and intensity of other types of storms.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #9/11	**Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Nearly all studies to date published in the peer-reviewed literature agree that global sea level has risen during the past century, and that it will continue to rise over the next century. Tide gauges throughout the world have documented rising sea levels during the last 130 years. This rise has been further confirmed over the past 20 years by satellite observations, which are highly accurate and have nearly global coverage. Recent studies have shown current sea level rise rates are increasing (Kemp et al. 2012; Parris et al. 2012) and project that future sea level rise over the rest of this century will be faster than those of the last 100 years (Parris et al. 2012; Willis et al. 2010).
New information and remaining uncertainties	The key issue in predicting future rates of global sea level rise is to understand and predict how ice sheets in Greenland and Antarctica will react to a warming climate. Current projections of global sea level rise do not account for the complicated behavior of these giant ice slabs as they interact with the atmosphere, the ocean and the land. Lack of knowledge about the ice sheets and their behavior is the primary reason that projections of global sea level rise includes such a wide range of plausible future conditions. Early efforts at semi-empirical models suggested much higher rates of sea level rise (as much as 6 feet by 2100) (Jevrejeva et al. 2010; Vermeer and Rahmstorf 2009). More recent semi-empirical models have suggested upper bounds closer to 3 or 4 feet (Jevrejeva et al. 2012; Rahmstorf et al. 2012). It is not clear, however, whether these statistical relationships will hold in the future. More recent work suggests that a high-end of 3 to 4 feet is more plausible. (Gladstone et al. 2012; Jevrejeva et al. 2012; Joughin et al. 2010; Katsman et al. 2011; Rahmstorf et al. 2012). Some decision makers may wish to consider a broader range of scenarios such as 8 inches or 6.6 feet by 2100 in the context of risk-based analysis (Burkett and Davidson 2012; Parris et al. 2012) .
Assessment of confidence based on evidence	Given the evidence and uncertainties, confidence is **very high** that global sea level has risen during the past century, and that it will continue to rise over this century. Given the evidence and uncertainties about ice sheet dynamics, confidence is **high** that the rate of global sea level rise has been faster since the early 1990s, but there is **medium** confidence in global sea level rise will be in the range of 1 to 4 feet by 2100.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #10/11	**Rising temperatures are reducing ice on land, lakes, and sea. This loss of ice is expected to continue.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. There have been a number of publications reporting decreases in ice on land (Fettweis et al. 2011) and glacier recession . Evidence that winter lake ice and summer sea ice are rapidly declining is based on satellite data and is incontrovertible (for lake ice Arctic Monitoring and Assessment Programme 2011; Wang et al. 2012). Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining and that if heat-trapping gas concentrations continue to rise, an essentially ice-free Arctic ocean will be realized sometime during this century (e.g., Stroeve et al. 2012; KM 10). September 2012 has the lowest levels of Arctic ice in recorded history. Great Lakes ice should follow a similar trajectory. Glaciers will generally retreat, except for a small percentage of glaciers that experience dynamical surging (Arctic Monitoring and Assessment Programme 2011). The rate of permafrost degradation is complicated by changes in snow cover and vegetation.
New information and remaining uncertainties	A key issue (uncertainty) is the rate of sea-ice loss through this century, which stems from a combination of large differences in projections between different climate models, natural climate variability and future rates of fossil fuel emissions. This uncertainty is illustrated in the figure showing the CMIP5-based projections (from Stroeve et al. 2012). Viable avenues to improving the information base are determining the primary causes of the range of different climate model projections and determining which climate models exhibit the best ability to reproduce the observed rate of sea ice loss.
Assessment of confidence based on evidence	Given the evidence base and uncertainties, confidence is **very high** that rising temperatures are melting sea ice, lake ice, and glaciers and that this melting is expected to continue. Given the evidence base and uncertainties, confidence is **high** that rising temperatures are thawing permafrost and that this thawing is expected to continue.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 2: Climate Science

Key Message Process: See KM#1.

Key message #11/11	**The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually and are becoming more acidic as a result, leading to concerns about potential impacts on marine ecosystems.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Technical Input reports (82) on a wide range of topics were also reviewed; they were received as part of the Federal Register Notice solicitation for public input. Work done by LeQuere et al. 2009 reported that the oceans currently absorb a quarter of anthropogenic CO_2. Publications have shown that this absorption causes the ocean to become more acidic (Doney et al. 2009). Recent publications demonstrate the adverse effects further acidification will have on marine life (Doney et al. 2012; Fabry et al. 2009; Gruber et al. 2012; Orr et al. 2005).
New information and remaining uncertainties	The key issue is to understand how future levels of ocean acidity will affect marine ecosystems. Absorption of anthropogenic CO_2, reduced pH, and lower calcium carbonate (CaCO3) saturation in surface waters, where the bulk of oceanic production occurs, are well verified from models, hydrographic surveys, and time series data(Orr et al. 2005).
Assessment of confidence based on evidence	**Very high** for trend of ocean acidification; **low-to-medium** for ecological consequences. Our present understanding of potential ocean acidification impacts on marine organisms stems largely from short-term laboratory and mesocosm experiments; consequently, the response of individual organisms, populations, and communities to more realistic gradual changes is largely unknown. Given the evidence base and uncertainties, confidence is **very high** that oceans are absorbing a quarter of emitted CO2.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Introduction to the Sectors

Every sector of the U.S. economy is affected in some way, either directly or indirectly, by climate changes, including changes in temperature, rising sea levels, and more extreme precipitation events and droughts. But none of these sectors exist in isolation, and each sector connects directly and indirectly to other sectors. Forestry activities affect, and are affected by, water supply, changing ecosystems, impacts to biological diversity, and energy availability. Water supply and energy use are completely intertwined, since water is used to generate energy and energy is used to pump, treat, and deliver water. Human health is affected by water supply, agricultural practices, transportation systems, energy availability, and land use – among other factors. Human social systems and communities are also directly affected by extreme weather events and changes in natural resources like water; they are also affected both directly and indirectly by ecosystem health.

The 2013 National Climate Assessment addresses some of these topics individually, and others using a cross-sectoral approach that focuses on the climate-related risks and opportunities that occur across sectors – as well as within them. For example, there are specific chapters focusing on water, energy production and use, agriculture, human health, and ecosystems and biological diversity. Six cross-cutting chapters address how climate change can interact with multiple sectors. These cover the following topics:

- Water, energy, and land use
- Tribal culture, lands, and resources
- Land use and land cover
- Biogeochemical cycles and implications for ecosystems
- Rural communities
- Urban infrastructure and vulnerability

A common thread across these chapters is the connections across the sectors and the way that changes in one sector are amplified or attenuated through connections with other sectors. Another theme considers how decisions that people make daily can influence a cascade of events that affect individual and national vulnerability and/or resiliency to climate changes across multiple sectors. This “systems approach” tries to connect, for example, how adaptation and mitigation strategies are themselves dynamic and interrelated systems that intersect with the sectors described here, like the way adaptation plans for future coastal infrastructure are correlated to the kinds of mitigation strategies that are put into place today. These chapters also address the importance of underlying vulnerabilities and the ways they may influence the risks associated with climate change.

The chapters in the following section start with an assessment of what is at risk within the selected sectors, and include both observations of existing impacts associated with climate change and impacts that are expected to result from climatic changes projected by climate models.

3. Water Resources

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The cycle of life is intricately joined with the cycle of water.
Jacques-Yves Cousteau

Key Messages

Climate Change Impacts on the Water Cycle

1. **Annual precipitation and runoff increases are observed now in the Midwest and Northeast regions and are projected to continue or develop in northern states; decreases are observed and projected in southern states.**
2. **Summer droughts are expected to intensify in most regions of the U.S., with longer term reductions in water availability in the Southwest, Southeast, and Hawai'i in response to both rising temperatures and changes in precipitation.**
3. **Floods are projected to intensify in most regions of the U.S., even in areas where average annual precipitation is projected to decline, but especially in areas that are expected to become wetter, such as the Midwest and the Northeast.**
4. **Expected changes in precipitation and land use in aquifer recharge areas, combined with changes in demand for groundwater over time, will affect groundwater availability in ways that are not well monitored or understood.**
5. **Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to challenge the sustainability of coastal freshwater aquifers and wetlands.**
6. **Air and water temperatures, precipitation intensity, and droughts affect water quality in rivers and lakes. More intense runoff and precipitation generally increase river sediment, nitrogen, and pollutant loads. Increasing water temperatures and intensifying droughts can decrease lake mixing, reduce oxygen in bottom waters, and increase the length of time pollutants remain in water bodies.**

Climate Change Impacts on Water Resources

7. **In the Southwest, parts of the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai'i, surface and groundwater supplies are already affected and are expected to be reduced further by declining runoff and groundwater recharge trends, increasing the likelihood of water shortages for many off-stream and in-stream water uses.**
8. **Increasing flooding risk affects human safety and health, property, infrastructure, economy, and ecology in many basins across the U.S.**
9. **In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.**
10. **Increasing resilience and enhancing adaptive capacity are useful strategies for water resources management and planning in the face of climate change. Challenges include: competing demands for water; a variety of institutional constraints; lack of scientific information or access to it; considerable scientific and economic uncertainties; inadequate information useful for practical applications; and difficulties in engaging stakeholders.**

Climate Change Impacts on the Water Cycle

Water cycles constantly from the atmosphere to the land and the oceans (through precipitation and runoff) and back to the atmosphere (through evaporation, and the release of water to atmosphere through plant leaves, called "transpiration"), setting the stage for all life to exist. The water cycle is dynamic and naturally variable, and societies and ecosystems are adapted to this variability. However, climate change is altering the water cycle in multiple ways, presenting unfamiliar risks and opportunities.

Changing Rain, Snow, and Runoff

Annual precipitation and runoff increases are observed now in the Midwest and Northeast regions and are projected to continue or develop in the northern states; decreases are observed and projected in southern states.

Annual **average precipitation** over the continental U.S. as a whole increased by more than 2 inches (0.2 inches per decade) between 1895 and 2011 (Bales et al. 2012; NCDC 2011). In recent decades, annual average precipitation increases have been observed across the upper Midwest, northern Great Plains, and Northeast, moderate increases in the Northwest, and decreases in Hawai'i and parts of the Southeast and Southwest (IPCC 2007; NCDC 2011). Increases in the north and decreases in the Southwest are projected to continue in this century (Orlowsky and Seneviratne 2012).

Historically, the number and intensity of **heavy precipitation** events (top 1% or greater) have been increasing in all U.S. regions except the Southwest, Northwest, and Hawai'i. Further, the volume of precipitation from the heaviest daily events has increased across the U.S. (see Ch. 2:

Our Changing Climate). For example, during 1950-2007, daily precipitation totals with 2-, 5-, and 10-year return periods increased in the Northeast and western Great Lakes (DeGaetano 2009; Mishra and Lettenmaier 2011). Extreme daily precipitation events are projected to increase everywhere (see Ch. 2: Our Changing Climate), such that a heavy precipitation event that historically occurred once in 20 years would arrive as frequently as every 5 to 15 years by late in this century (Groisman et al. 2012; Wang and Zhang 2008).

Snowpack and snowmelt-fed rivers in much of the western U.S. have changed in response to warming trends since the middle of the last century, including the past decade (Fritze et al. 2011; Hoerling et al. 2012; Mote 2006; Pierce et al. 2008), showing declines in spring snowpack, earlier snowmelt-fed streamflow, more precipitation falling as rain instead of snow, and striking reductions in lake ice cover (Wang et al. 2012); several of these trends have now been shown to be due to human-induced warming trends (Barnett et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; Pierce et al. 2008; Ch. 2: Our Changing Climate). Similar historical trends have been observed in the northern Great Plains, Midwest, and Northeast. Permafrost is thawing in many parts of Alaska, a trend that not only affects habitats and infrastructure, but also mobilizes subsurface water and reroutes surface water in ways not previously witnessed (Romanovsky et al. 2011; Smith et al. 2010). All of these trends are projected to become even more pronounced as the climate continues to warm.

Changes in Snow, Runoff, and Soil Moisture

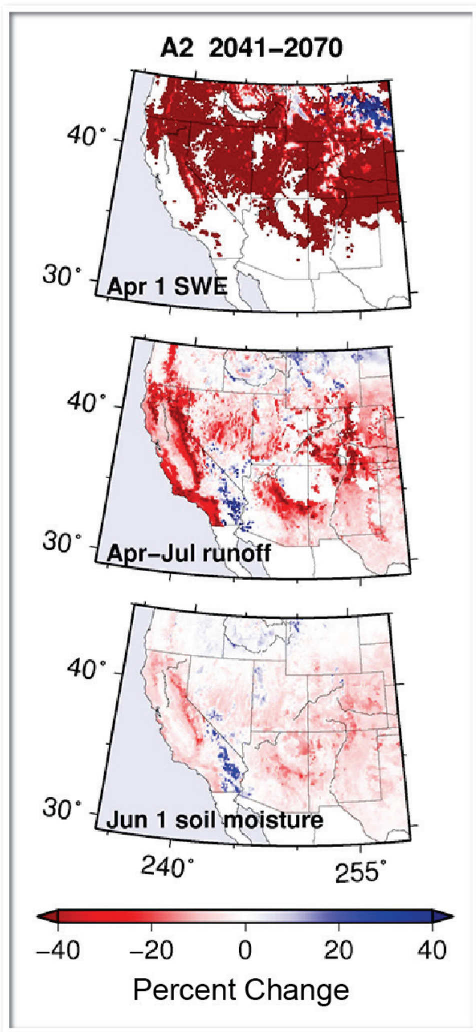

Figure 3.1: Changes in Snow, Runoff, and Soil Moisture

Caption: These projections, assuming continued increases in heat-trapping gas emissions (A2 scenario), illustrate: a) major losses in the water content of snowpack that fills western rivers (snow water equivalent, or SWE); b) significant reductions in runoff in California, Arizona, and the Central Rocky Mountains; and c) reductions in soil moisture across the Southwest. The changes shown are for mid-century (2041-2070) as percentage changes from 1970-2000 conditions (Cayan et al. 2012).

Evapotranspiration (evaporation of water from soil and the release of water to the air from plant leaves) is the second largest component of the water cycle after precipitation. The evapotranspiration process responds to both solar energy and moisture availability at the land surface and regulates the amounts of soil moisture, groundwater recharge, and runoff (Mueller et al. 2011). This coupling of energy and water processes complicates the estimation of regional evapotranspiration and its modeling. Actual evapotranspiration depends on the potential of the atmosphere to absorb water vapor as well as on water availability for evapotranspiration at the land surface. The atmospheric potential for evapotranspiration is generally strongly dependent on temperature (Vautard et al. 2010); however, even though the Earth's surface temperature increased during the past 50 years, potential evaporation rates (as measured by pan-evaporation) have declined in many places (Peterson et al. 1995), including the U.S. (Roderick and Farquhar 2002). Decreasing wind speed (Vautard et al. 2010) has been proposed as a factor for this decreased evaporative demand (McVicar et al. 2012), while reduced solar irradiance at the land surface associated with increased cloud cover and aerosol concentration (Roderick and Farquhar 2002) and increasing humidity have also been identified as possible contributing factors in other parts of the globe (McVicar et al. 2012). In addition to the factors controlling evaporative demand, *actual* evapotranspiration also depends on the availability of soil moisture, which appears to have been declining over much of North America during the past few decades (BAMS 2012). However, much more research is needed to confidently identify historical trends, causes, and implications for future evapotranspiration trends. This represents a critical uncertainty in projecting the impacts of climate change on regional water cycles.

Soil moisture, on a regional scale, has historically been difficult to monitor and has often been inferred from models, but it is well-recognized that soil moisture plays a major role in the water cycle. In the last 20 years, soil moisture appears to have declined in parts of the Southeast (Georgakakos and Zhang 2011; Hamlet et al. 2007), southern Great Plains, and Southwest, and increased in the Northeast (Liu et al. 2011; Su et al. 2010). Based mostly on hydrologic simulations, soil moisture, especially in summer, is expected to decline with higher temperatures and attendant increases in the potential for evapotranspiration in much of the country, especially in the Southwest (Cayan et al. 2010; Ch. 2: Our Changing Climate) and Southeast (Georgakakos and Zhang 2011; Wehner et al. 2011).

Runoff and streamflow, at regional scales, declined during the last century in the Northwest (Luce and Holden 2009) and increased in the Mississippi basin and Northeast, with no clear trends in much of the rest of the continental U.S. (McCabe and Wolock 2011). Annual runoff in the Colorado River Basin has declined (U.S. Bureau of Reclamation 2011c), although tree-ring studies in the Colorado River basin and Southeast U.S. indicate that these regions have experienced even drier conditions in the past two thousand years (Hoerling et al. 2012; Meko et al. 2007; Woodhouse et al. 2006). Similarly, runoff from the Missouri River basin was greater and less variable during the 20th century than in previous centuries (Watson et al. 2009). Projected changes in runoff for eight basins in the Pacific Northwest, northern Great Plains, and Southwest are illustrated below.

Streamflow Projections for River Basins in the Western U.S.

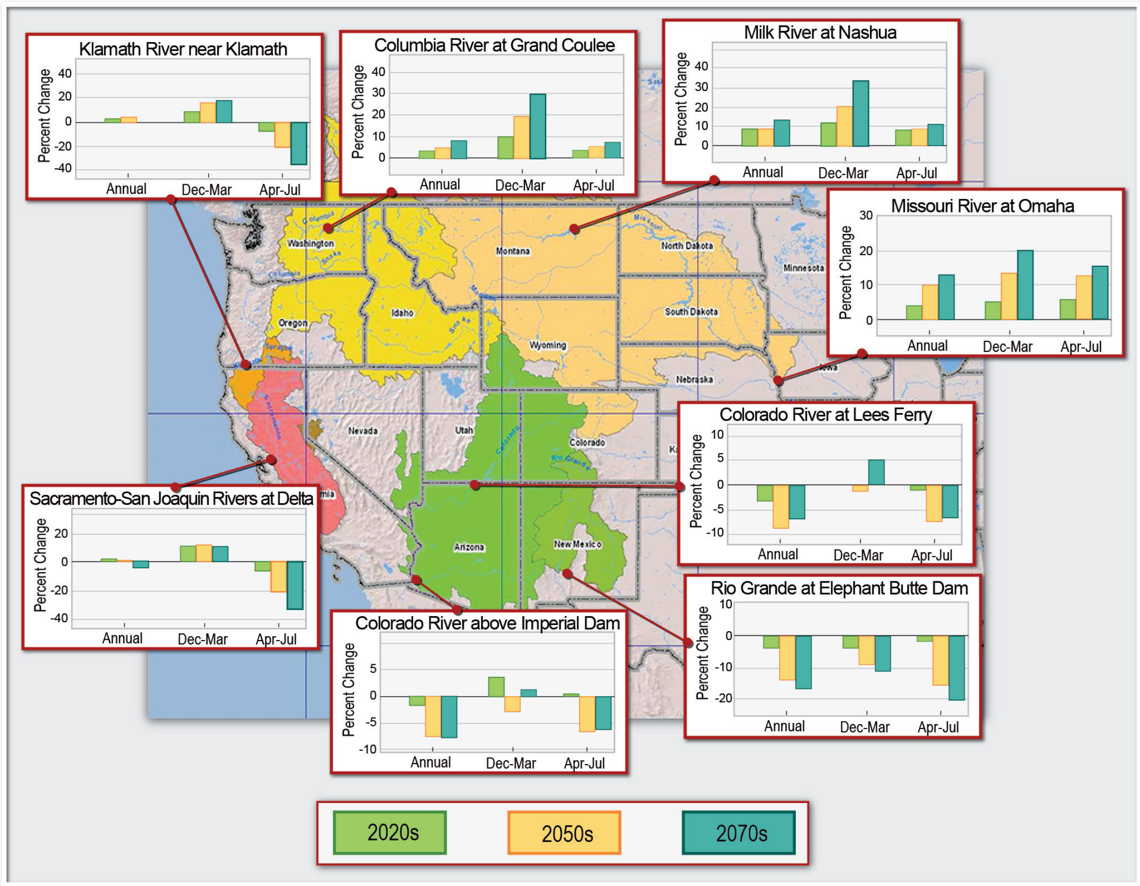

Figure 3.2: Streamflow Projections for River Basins in the Western U.S.

Caption: Streamflow projections associated with an ensemble of emissions scenarios and climate projections for eight river basins in the western U.S. The panels show percentage changes in average runoff, with projected increases above the zero line and decreases below. Projections are for annual, cool, and warm seasons, for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s).

Basins in the southwestern U.S. to southern Rockies (for example, the Rio Grande and Colorado River basins) are projected to experience gradual runoff declines during the this century, while basins in the Northwest to north-central U.S. (for example, the Columbia and the Missouri River basins) are projected to experience little change through the middle of this century, and increases by late this century.

Projected changes in runoff differ by season, with cool season runoff increasing over the west coast basins from California to Washington and over the north-central U.S. (for example, the San Joaquin, Sacramento, Truckee, Klamath, Missouri, and Columbia River basins). Basins in the southwestern U.S. to southern Rockies (for example, the Colorado and Rio Grande River basins) are projected to see little change to slight decreases in the winter months.

Warm season runoff is projected to decrease substantially over a region spanning southern Oregon, the southwestern U.S., and southern Rockies (for example, the Klamath, Sacramento, San Joaquin, Truckee, Rio Grande, and the Colorado River basins), and change little or increase slightly north of this region (for example, the Columbia and Missouri River basins). The projected streamflow changes and associated uncertainties have water management implications, as the existing management systems have been designed to operate within the historical range of variability. (Source: U.S. Bureau of Reclamation 2011a).

Summer Droughts Intensify

Summer droughts are expected to intensify in most regions of the U.S., with longer-term reductions in water availability in the Southwest, Southeast, and Hawai'i in response to both rising temperatures and changes in precipitation.

Averaged over recent climate models, annual runoff and streamflow are projected to decline in the Southwest (Milly et al. 2008; U.S. Bureau of Reclamation 2011b) and Southeast (Georgakakos and Zhang 2011), and to increase in the Northeast, Alaska, Northwest, and upper Midwest regions (Brekke 2011; Elsner et al. 2010; IPCC 2007; Markstrom et al. 2011; Milly et al. 2008; Moser et al. 2008; U.S. Bureau of Reclamation 2011b). Broadly, as warming changes the water cycle processes, the amount of runoff generated by each unit of precipitation is expected to decline (McCabe and Wolock 2011).

There has been no universal trend in the overall extent of drought across the continental U.S. since 1900. However, in the Southwest, there has been a trend towards more widespread drought during the 1901 to 2010 period, reflecting both precipitation deficits and higher temperatures (Hoerling et al. 2012). Drought conditions are also projected to increase in the Southeast, Hawai'i, and the Pacific Islands. Generally – except where increases in summer precipitation compensate – summer droughts (see Ch. 2: Our Changing Climate) are expected to intensify almost everywhere in the continental U.S. (Trenberth et al. 2004). Basins watered by glacial melt in the Sierra Nevada, Glacier National Park, and Alaska may experience increased summer streamflows in the short term, until the amounts of glacial ice become too small (Basagic and Fountain 2011; Hall and Fagre 2003; Hodgkins et al. 2005).

Floods Intensify in Most Regions

Floods are projected to intensify in most regions of the U.S., even in areas where average annual precipitation is projected to decline, but especially in areas that are expected to become wetter, such as the Midwest and the Northeast.

Heavy precipitation increased over recent decades (Gutowski et al. 2008; Karl and Knight 1998) in most regions of the country, but **floods** are basin specific and dependent on existing moisture conditions among other factors. Annual flood magnitude trends (see figure in Ch. 2: Our Changing Climate) generally follow annual streamflow, except for the Northwest where there has been no trend in annual flood magnitude. Annual peak flows have increased at gauges in the upper Midwest and in the Northeast during the past 85 years, and have declined in the Rocky Mountains and the Southwest U.S., with other regions showing no consistent trends (Hirsch and Ryberg 2012). Seasonality of precipitation and antecedent conditions (especially soil moisture) are important determinants of runoff volume. If storms continue to intensify and catchment areas receive increasingly more precipitation as rain rather than snow, or more rain on snowpacks (Knowles et al. 2006; McCabe et al. 2007; Mote 2003, 2006), floods in some cases are expected to increase – even where precipitation and overall stream flows decline (see Ch. 2: Our Changing Climate).

Groundwater Availability

Expected changes in precipitation and land use in aquifer recharge areas, combined with changes in demand for groundwater over time, will affect groundwater availability in ways that are not well monitored or understood.

Groundwater storage or flow responses to climate change are not well understood. Despite their critical national importance as water supply sources, aquifers are not generally monitored in ways that allow for clear identification of climatic influences on groundwater storage or flows. Nearly all monitoring is focused in areas and aquifers where variations are dominated by groundwater pumping, which largely masks climatic influences (Hanson et al. 2006). In addition, climate models do not, in general, yet include dynamic representations of the groundwater reservoir and its connections to streams, the soil-vegetation system, and the atmosphere, hampering progress in understanding the potential impacts on groundwater and groundwater-reliant systems of climate change (Fan et al. 2007; Maxwell and Kollet 2008; Schaller and Fan 2009). Thus far, there have been few observations and projections of groundwater responses to climate change (Hanson et al. 2012), but surface water declines already have resulted in higher groundwater use in some areas (for example, in the Central Valley of California and the Southeast) and even more stress on both groundwater and surface water systems (NRC 2004). In many mountainous areas of the U.S., groundwater recharge derives disproportionately from snowmelt infiltration (Earman et al. 2006), suggesting that the loss of snowpack is likely to disrupt or change recharge rates and patterns (Earman and Dettinger 2011).

Spotlight on Groundwater
Groundwater is the only perennial source of fresh water in many regions and provides a buffer against climate extremes. As such it is essential to water and food security and in sustaining ecosystems. Over the 2001 to 2008 period, the groundwater depletion rate was estimated at 145 ±39 km^3/yr worldwide, and 26±7 km^3/yr in North America (Konikow 2011; Taylor et al. 2012). Though groundwater occurs in most areas of the U.S., the capacity of aquifers to store water varies depending on the geology of the region.

During the 2006 – 2009 California drought, when the source of irrigation shifted from surface water to predominantly groundwater, the groundwater storage in the California Central Valley declined by 24 km^3 to 31 km^3, equivalent to the storage capacity of Lake Mead, the largest reservoir in the U.S. (Famiglietti et al. 2011).

As the risk of drought increases, groundwater can play a key role in enabling adaptation to climate variability and change – for example, through conjunctive management strategies that use surface water for irrigation and water supply during wet periods, and groundwater during drought. However, the current understanding of the dynamic relationship between groundwater and climate is limited by the dearth of measurements of groundwater recharge and discharge variations and changes.

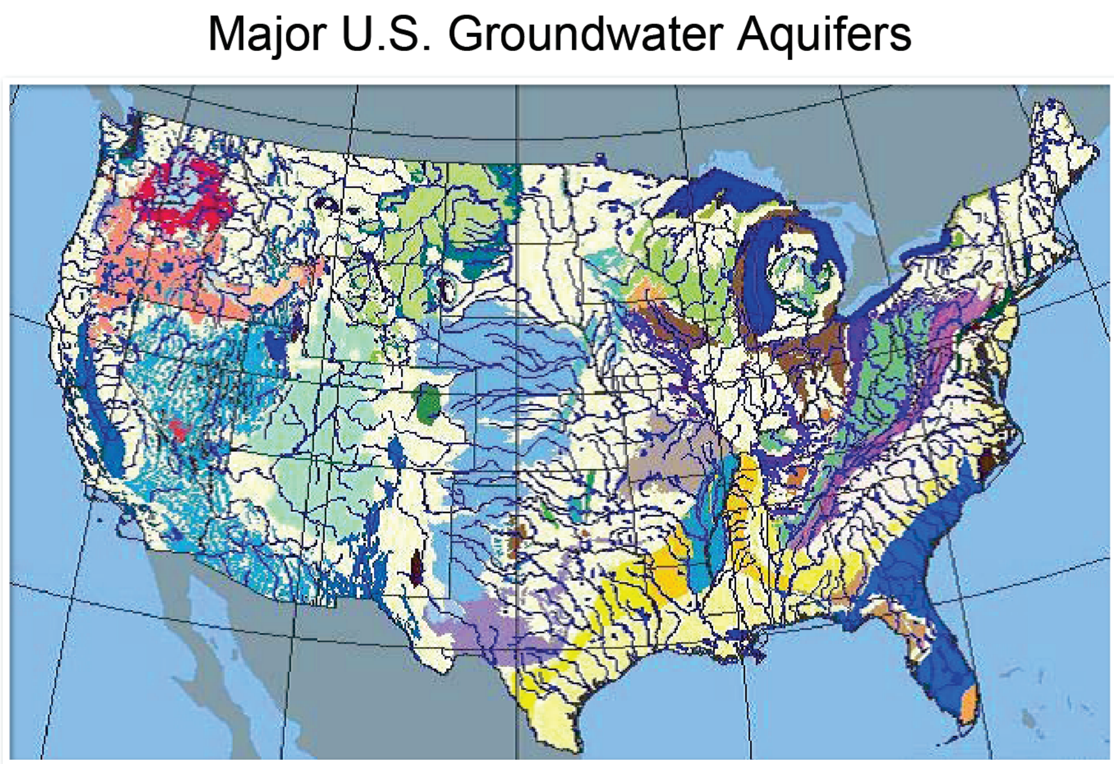

Figure 3.3: Major U.S. Groundwater Aquifers

Caption: Groundwater aquifers are found throughout the U.S., but they vary dramatically in terms of ability to store and recharge water. On this map, differences in geology are illustrated: blue is unconsolidated sand and gravel; yellow is semi-consolidated sand; green is sandstone; brown is carbonate-rock; and red is igneous and metamorphic rock.

(Source: DOI 2012)

Risks to Coastal Aquifers and Wetlands

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to challenge the sustainability of coastal freshwater aquifers and wetlands.

With so much of the nation's population concentrated near coasts, coastal aquifers and wetlands are precious resources. These aquifers and wetlands, which are extremely important from a biological/biodiversity perspective (see Ch. 8: Ecosystems and Biodiversity, Ch. 25: Coastal Zone), may be particularly at risk due to the combined effects of inland droughts, increased surface water impoundments and diversions, increased groundwater pumping, and accelerating sea level rise and greater storm surges (Chang et al. 2011; Heimlich and Bloetscher 2011). Several coastal areas (see Ch. 25: Coastal Zone), including Apalachicola Bay in Florida, the Mississippi River delta in Louisiana, and the delta of the Sacramento-San Joaquin rivers in northern California, are particularly vulnerable.

Lakes and Rivers at Risk

Air and water temperatures, precipitation intensity, and droughts affect water quality in rivers and lakes. More intense runoff and precipitation generally increase river sediment, nitrogen, and pollutant loads. Increasing water temperatures and intensifying droughts can decrease lake mixing, reduce oxygen in bottom waters, and increase the length of time pollutants remain in water bodies.

Water temperature has increased in many rivers (Kaushal et al. 2010), a trend generally expected to persist with climate warming (Cloern et al. 2011; Van Vliet et al. 2011). Thermal lake and reservoir stratification is increasing with increased air and water temperatures (Sahoo and Schladow 2008; Sahoo et al. 2012; Schneider and Hook 2010), and mixing may be eliminated in shallow lakes, decreasing dissolved oxygen and releasing excess nutrients (nitrogen and phosphorous), heavy metals (such as mercury), and other toxics into lake waters (Sahoo and Schladow 2008; Sahoo et al. 2012; Schneider and Hook 2010).

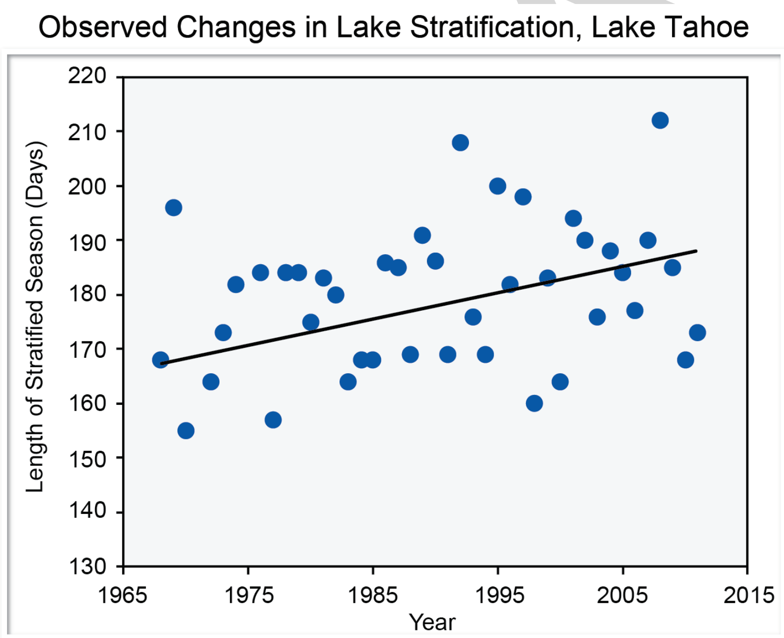

Figure 3.4: Observed Changes in Lake Stratification, Lake Tahoe

Caption: Thermal stratification of lakes, in this case, Lake Tahoe, has been increasing since the 1960s in response to increasing air and surface water temperatures. Temperature differences cause changes in density, leading to longer stratification seasons (on average, by 20 days in Lake Tahoe), decreasing the opportunities for deep lake mixing, reducing oxygen levels, and causing impacts to many species and numerous aspects of aquatic ecosytems. (UC Davis and Tahoe Environmental Research Center 2012)

Increased low flows under drought conditions as well as increased overland flow during floods have the potential to worsen water quality. Increasing precipitation intensity, along with the effects of wildfires and fertilizer use, are increasing sediment, nutrient, and contaminant loads in surface waters for downstream water users (Pruski and Nearing 2002a, 2002b) and ecosystems. Mineral weathering products, like calcium, magnesium, sodium, and silicon and nitrogen loads (Justic et al. 2005; McIsaac et al. 2002) have been increasing with higher streamflows (Godsey et al. 2009). Changing land cover, flood frequencies, and flood magnitudes are expected to increase mobilization of sediments in large river basins (Osterkamp and Hupp 2010). Changes in sediment transport will vary regionally and by land-use type, but may increase by 25% to 55% over the next century (Nearing et al. 2005). Increased frequency and duration of droughts, and associated low water levels, increase nutrient concentrations and residence times in streams, potentially increasing the likelihood of harmful algal blooms and low oxygen conditions (Whitehead et al. 2009).

Climate Change Impacts on Water Resources

Climate change-induced water cycle changes are affecting water supplies in a variety of ways that affect ecosystems and livelihoods by altering reliability of water availability, demand, competition between sectors, and management responses in many regions. The direction and magnitude of the projected impacts are expected to vary by type of use, region, and adaptation responses.

Water benefits derive from freshwater withdrawals (from streams, rivers, lakes, and aquifers) for municipal, industrial, agricultural, and re-circulating electric power plant cooling water supply (*off-stream* water uses). Water benefits also come from *in-stream* water flows, levels, and quality suitable for hydropower production, once-through electric power plant cooling water supply, navigation, recreation, and healthy ecosystems. Climate change, acting concurrently with demographic, land-use, energy generation and use, and socioeconomic changes, is challenging existing water management practices by affecting water availability and demand and by exacerbating competition among uses and users (see Ch. 13: Land Use and Land Cover Change, Ch. 4: Energy Supply and Use, and Ch. 6: Agriculture). In some regions, these current and expected impacts are hastening efficiency improvements in water withdrawal and use, the deployment of more proactive water management and adaptation approaches, and the re-assessment of the water infrastructure and institutional responses (Bales et al. 2012).

Off-stream Water Uses

At the national level, total freshwater withdrawals (including both water that is withdrawn and eventually consumed and amounts that return to the original surface or groundwater source) and consumptive uses have leveled off since 1980 at 350 and 100 billion gallons per day respectively, despite the addition of 68 million people from 1980 to 2005 (Kenny et al. 2009). Irrigation and all electric power plant cooling withdrawals currently account for approximately 77% of total withdrawals, municipal and industrial for 20%, and livestock and aquaculture for 3%. Most thermoelectric withdrawals are returned back to rivers after cooling, while most irrigation withdrawals are used up by the processes of evapotranspiration and plant growth. Thus, consumptive water use is dominated by irrigation (81%) followed distantly by municipal and industrial (8%) and the remaining water uses (5%).

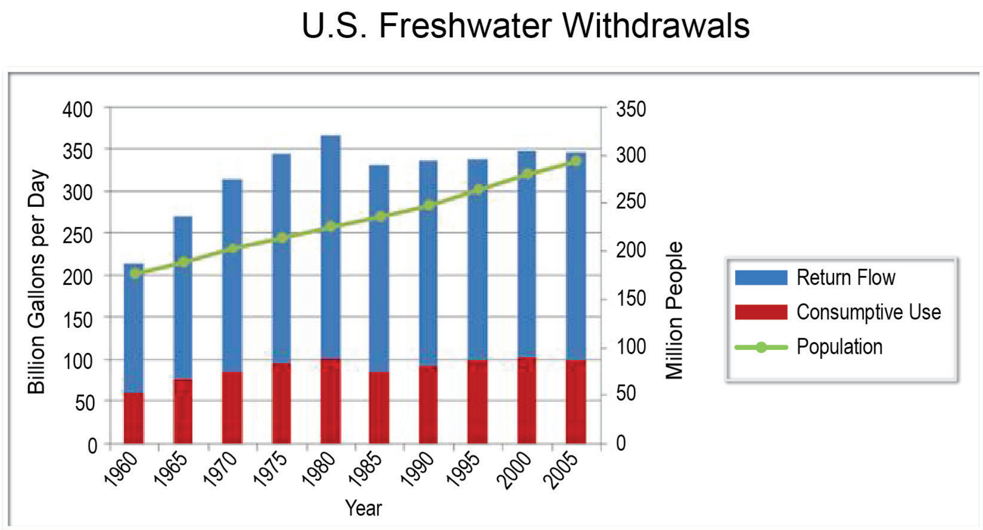

Figure 3.5: U.S. Freshwater Withdrawals

Caption: Trends in total freshwater withdrawal (equal to the sum of consumptive use and return flows to rivers) and population in the contiguous U.S. This graph illustrates the remarkable change in the relationship between water use and population growth since about 1980. Reductions in per capita water withdrawals are directly related to increases in irrigation efficiency for agriculture; more efficient cooling processes in electrical generation; and, in many areas, reductions in exterior landscape watering in commercial and residential properties. While efficiency improvements have effectively decoupled water use from population growth and have resulted in more flexibility in meeting water demand, in some cases they have also reduced the flexibility to scale back water use in times of drought. With drought stress projected to increase in summer months in most of the U.S., drought vulnerability is also expected to rise (Bales et al. 2012).

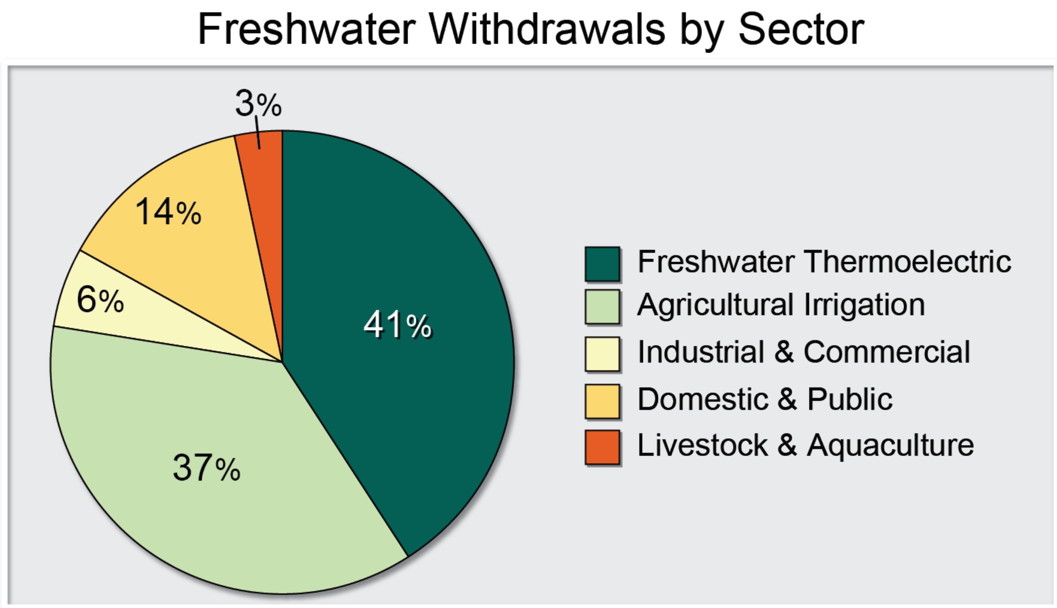

Figure 3.6: Freshwater Withdrawals by Sector

Caption: Total water withdrawals in the U.S. are dominated by agriculture and energy production, though the primary use of water for thermoelectric production is for cooling, where water is often returned to lakes and rivers after use (return flows) (Figure source: USGS, 2005.)

Per capita water withdrawal and use are decreasing due to many factors, including (Brown et al. 2012): demand management, efficiency improvement programs, and pricing strategies (Groves et al. 2008; Jeffcoat et al. 2009; Rockaway et al. 2011) (*in the municipal sector*); changes from water intensive manufacturing and other heavy industrial activities to service-oriented businesses (David 1990), and enhanced water use efficiencies in response to environmental pollution legislation (*in the industrial and commercial sector*); replacement of older once-through-cooling electric power plants by plants that recycle their cooling water (*in the thermoelectric sector*); switching from flood irrigation to more efficient methods in the western U.S. (Brown 2000; Foti et al. 2012a) (*in the irrigation sector*); and decreasing consumer demands for meat (Haley 2001) (*in the livestock sector*). Notwithstanding the overall national trends, regional water withdrawal and use are strongly correlated with climate (Balling and Gober 2007); hotter and drier regions tend to have higher per capita usage, and water demand is affected by both temperature and precipitation on a seasonal basis.

In the absence of climate change but in response to a projected 60% to 85% population increase, simulations indicate that the demand for water withdrawals in the U.S. will increase respectively by 3% to 8% over the next 50 years (Foti et al. 2012; USFS 2012). If, however, climate-change projections are also factored in, the increase in demand for water withdrawals has been estimated to rise by 25% to 35% (Foti et al. 2012) over the same period, with three-quarters of the increase attributed to irrigation demand and the rest to landscape watering and electricity generation.

Projected Changes in Water Withdrawal

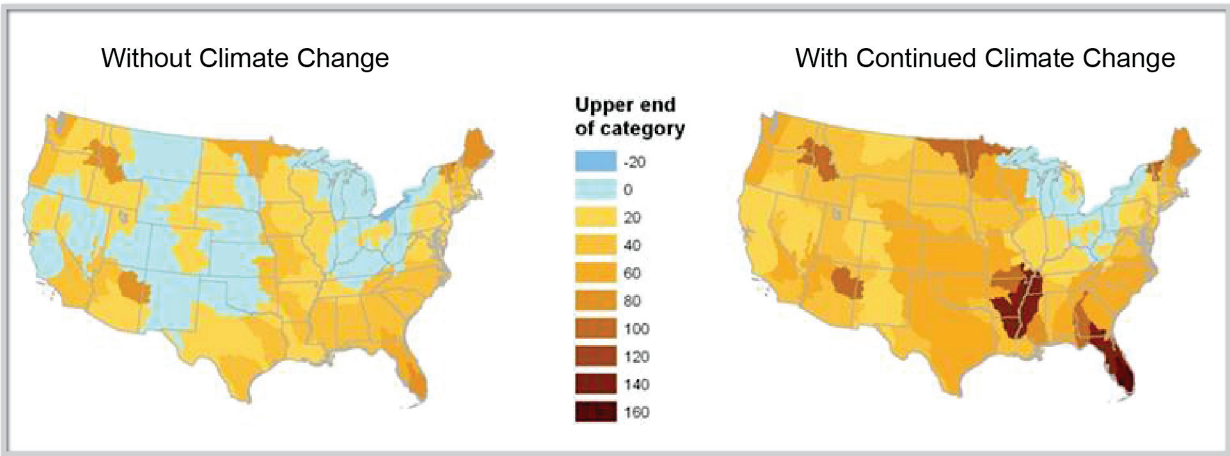

Figure 3.7: Projected Changes in Water Withdrawals

Caption: Percent change from 2005 to 2060 in projected withdrawals assuming no change in climate (left) and continued growth in heat-trapping gas emissions (A2 scenario, right). The effects of climate change, primarily associated with increasing temperatures, are projected to significantly increase water demand across most of the U.S. (Foti et al. 2012).

Power plant cooling is expected to be affected by changes in water supply availability in areas where surface water supplies are diminishing and by increasing water temperatures. Higher water temperatures affect both the effectiveness of electric generation and cooling processes and the ability to discharge heated water to streams from once-through cooled power systems due to regulatory requirements and concerns about ecosystem impacts (see Ch. 4: Energy Supply and Use) (Wilbanks and al. 2007)).

Flooding and Instream Water Uses

Extreme precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Reported flood frequency and severity increases are generally consistent with observed and projected water cycle changes in many U.S. regions (Brekke et al. 2009a; Das et al. 2012; Raff et al. 2009; Shaw and Riha 2011; Walker et al. 2011), especially in the Northeast and Midwest. This trend, combined with the devastating toll of large floods (in human life, property, environment, and infrastructure; see "Spotlight on Flooding"), suggests that proactive management measures could minimize changing future flood risks and consequences. New York, Boston, Miami, Savannah, New Orleans, the San Francisco Bay area, and many other U.S. cities located along coasts are threatened by flooding and seawater intrusion due to sea level rise. Increasing flooding risk may also increase health risk, and poses safety risks, when critical infrastructure fails (Ebi et al. 2006; Kessler 2011; Patz et al. 2000; Wright et al. 2012). Though numerous flood risk reduction measures are possible, including levees, land-use zoning, flood insurance, and restoration of natural flood plain retention capacity (FEMA 1994), economic conditions may constrain implementation. The effective use of these measures would require significant investment in many cases, as well as updating policies and methods to account for climate change (Milly et al. 2008; Villarini et al. 2011) in the planning, design, operation, and maintenance of flood risk reduction infrastructure (Brekke et al. 2009a; Yang 2010).

Spotlight on Flooding

The 2011 floods in the Northeast and the Mississippi basin, and the 2009 floods in the Southeast set new precipitation and flood stage records in many locations, causing fatalities, property damage, and devastating economic losses of several billion dollars.

There was widespread flooding along the Susquehanna River in Binghamton, N.Y. in September 2011, disrupting road and rail transportation (*top*; photo credit: NWS Forecast Office, Binghamton, NY); the Fort Calhoun Nuclear Power Plant in eastern Nebraska was surrounded by a Missouri River flood, June 8, 2011, that also affected Louisiana, Mississippi, Missouri, Illinois, Kentucky, Tennessee, and Arkansas (*middle*; photo credit: Larry Geiger); and the R.M. Clayton sewage treatment plant in Atlanta, Georgia, September 23, 2009, was engulfed by floodwaters forcing it to shut down and discharge raw sewage into the Chattahoochee River.

The 2009 Southeast floods affected several counties throughout northern Georgia (*bottom*; photo credit: NASA), Tennessee, Alabama, Mississippi and Arkansas, caused eleven fatalities, and cost more than a billion dollars (NOAA, Southeast Floods, 18-23 2009). Interestingly, the 2009 Southeast flood occurred in the wake of a record setting drought (2006-2008), illustrating the continuing potential high risks and vulnerabilities associated with both floods and droughts.

Hydropower contributes 6% of electricity generation nationwide, but up to 60% to 70% in the Northwest and 20% in California, Alaska, and the Northeast (EIA 2011). Climate change is expected to affect hydropower *directly* through changes in runoff (average, extremes, and seasonality) and *indirectly* through increased competition with other water uses. Based on runoff projections, hydropower is expected to decline in the southern U.S. (especially the Southwest) and increase in the Northeast and Midwest though actual gains or losses will depend on facility size and changes in runoff volume and timing. Where non-power water demands are expected to increase (as in the southern U.S.), hydropower generation, dependable capacity, and ancillary services are likely to decrease. One-quarter of all hydropower facilities nationwide, especially in the Southeast, Southwest, and the Great Plains, are expected to face water availability constraints (EPRI 2011), and these challenges will rise as aging hydropower infrastructure needs to be replaced (Brekke 2011).

Inland **navigation**, most notably in the Great Lakes and the Missouri, Mississippi, and Ohio River systems, is particularly important for agricultural commodities (transported from the Midwest to the Gulf coast and on to global food markets), coal, and iron ore (Bales et al. 2012; DOT 2011). Navigation is affected by ice cover and by floods and droughts. Seasonal ice cover on the Great Lakes has been decreasing (Wang et al. 2012) and may allow increased shipping (Millerd 2011). However, lake level declines are also possible in the long term, decreasing vessel draft and cargo capacity, but projections of lake levels are uncertain, with even the direction of change undetermined (see Ch. 18: Midwest and Ch. 6: Transportation). Similarly, although the river ice cover period has been decreasing (Hodgkins et al. 2005) (extending the inland navigation season), seasonal ice cover changes (Beltaos and Prowse 2009; Hawkes et al. 2010; Prowse et al. 2011; Weyhenmeyer et al. 2011) could impede lock operations (Hawkes et al. 2010). Intensified floods are likely to hinder shipping by causing waterway closures and damaging or destroying ports and locks. Intensified droughts can decrease reliability of flows or channel depth. Both floods and droughts can disrupt rail and road traffic and increase shipping costs (DOT 2012) and result in commodity price volatility (Ch. 19: Great Plains).

Recreation activities associated with water resources, including boating, fishing, swimming, skiing, camping, and wildlife watching, are a strong regional and national economic driver, valued at between $700 billion and $1.1 trillion annually (DOC 2012; U.S. Census Bureau 2012). Recreation is sensitive to weather and climate (Yu et al. 2009), and climate change impacts to recreation can be difficult to project (Scott and Becken 2010). Rising temperatures affect extent of snowcover and mountain snowpack, with impacts on skiing (Dawson et al. 2009) and snowmobiling (Frumhoff et al. 2008). As the climate warms, changes in precipitation and runoff are expected to result in both beneficial (in some regions) and adverse impacts (Yu et al. 2009) to water sports, with potential for considerable economic and job losses (Frumhoff et al. 2008; Union of Concerned Scientists 2009).

Changing climate conditions are projected to impact **water and wastewater treatment and disposal** in several ways, both positively and negatively. Elevated stream temperatures, combined with lower flows, may require wastewater facilities to increase treatment to meet stream water quality standards (EPA 2011). More intense precipitation and floods, combined with escalating urbanization and associated increasing impermeable surfaces, may amplify the likelihood of contaminated overland flow or combined sewer overflows (Whitehead et al. 2009).

Conversely, increasing, but not extreme, precipitation could result in increased stream flows, improving capacity to absorb wastewater in some regions. Sea level rise and more frequent coastal flooding could damage wastewater utility infrastructure and lower treatment efficiency (Flood and Cahoon 2011; Ch. 25: Coastal Zone).

Changes in streamflow temperature and flow regimes can affect **aquatic ecosystem** structure and function (see Ch. 8: Ecosystems and Biodiversity). Water temperature directly regulates the physiology, metabolism, and energy of individual aquatic organisms, as well as entire ecosystems. Streamflow quantity influences the extent of available aquatic habitats, and streamflow variability regulates species abundance and persistence. Flow also influences water temperature, sediment, and nutrient concentrations (Maurer et al. 2010). Hydrologic alterations due to human interventions have without doubt impaired riverine ecosystems in most U.S. regions and globally (Poff et al. 2010). If the rate of climate change (Loarie et al. 2009) outpaces plant and animal species adjustment to temperature change, additional biodiversity loss may occur. Furthermore, climate-induced water cycle alterations may exacerbate existing ecosystem vulnerability, especially in the western U.S. (Falke et al. 2011; Rood et al. 2008; Stromberg et al. 2010; Thomson et al. 2010) where droughts and shortages are likely to rise. But areas receiving additional precipitation, such as the northern Great Plains, may benefit.

Major Water Resource Vulnerabilities and Challenges

Many U.S. regions are expected to face increased drought and flood vulnerabilities and exacerbated water management challenges. This section highlights regions where such issues are expected to be particularly intense.

Drought is Affecting Water Supplies

In the Southwest, the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai‘i, surface and groundwater supplies are already affected and expected to be reduced by declining runoff and groundwater recharge trends, increasing the risk of water shortages for many off-stream and in-stream water uses.

Many southwestern and western watersheds, including the Colorado, Rio Grande (U.S. Bureau of Reclamation 2011b, 2011c; Ward et al. 2006), and Sacramento-San Joaquin (Brekke et al. 2009b; Connell-Buck et al. 2012; Georgakakos et al. 2012), are experiencing increasingly drier conditions with even larger runoff reductions (in the range of 10% to 20%) expected over some of these watersheds the next 50 years (Cayan et al. 2010). Declining runoff and groundwater recharge are expected to affect surface and groundwater supplies (Earman and Dettinger 2011) and increase the risk of water shortages for many off-stream and in-stream water uses. Changes in streamflow timing will exacerbate a growing mismatch between supply and demand (because peak flows are occurring earlier in the spring, while demand is highest in mid-summer) and will challenge the management of reservoirs, aquifers, and other water infrastructure (Rajagopalan et al. 2009). Rising stream temperatures and longer low flow periods may make electric power plant cooling water withdrawals unreliable, and may affect aquatic and riparian ecosystems by degrading habitats and favoring invasive, non-native species (Backlund et al. 2008).

Flood Effects on People and Communities

Increasing flooding risk affects human safety and health, property, infrastructure, economy, and ecology in many basins across the U.S.

Observations and projections suggest that heavy precipitation, peak flows, and flooding may become more frequent and intense in this century across the country and even more pronounced in the Midwest and Northeast, and that sea levels will continue to rise.

Flooding affects critical water, wastewater, power, transportation, and communications infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (see "Spotlight on Flooding"). Climate change and its impacts on water supply can result in both increased uncertainty and decreased accuracy of flood forecasting, in the short term (Raff et al. 2012) and long term (Brekke 2011). This will hinder effective preparedness (such as evacuations) and the effectiveness of structural and nonstructural flood risk reduction measures. Increasing flooding risk will also exacerbate human health risks associated with failure of critical infrastructure (Ebi et al. 2006; Huang et al. 2011; Kessler 2011; Patz et al. 2000; Wright et al. 2012), waterborne disease (Curriero et al. 2001; Ch. 9: Health), and airborne diseases (Ziska et al. 2008). Thus, effective climate change adaptation planning requires an integrated approach (Frumhoff et al. 2008; Kundzewicz et al. 2002; Moser et al. 2008) that addresses public health and safety issues (City of New York 2012; Kirshen et al. 2008). The long lead time needed for the planning, design, and construction of critical infrastructure that provides resilience to floods means that consideration of long-term changes should begin soon. Lastly, in coastal areas, sea level rise may act in parallel with inland climate changes to exacerbate water use impacts and challenges (Obeysekera et al. 2011; Ch. 17: Southeast).

Water Resources Management

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.

Water managers and planners strive to balance water availability and demand and secure adequate supplies for all off-stream and in-stream water uses and users. The management process involves complex tradeoffs among water use benefits, consequences, and risks, and, by altering water availability *and* demand, climate change is likely to present new challenges. For example, the California Bay-Delta experience indicates that managing risks and sharing benefits requires re-assessment of very complex ecosystems, infrastructure systems, water rights, stakeholder preferences, reservoir operation strategies, and significant investments, all of which are subject to large uncertainties (NRC 2010, 2011b, 2012). To some extent, all U.S. regions are susceptible, but the Southeast and Southwest are highly vulnerable because climate change is projected to reduce water availability, increase demand, and exacerbate shortages (see "Spotlight on Water Management").

Recent assessments illustrate the water management challenges facing California (Brekke et al. 2009b; Connell-Buck et al. 2012; Georgakakos et al. 2007; Georgakakos et al. 2012; Vicuna et al. 2010), the Southwest (Barnett and Pierce 2009; Rajagopalan et al. 2009), Southeast

(Georgakakos et al. 2010; Obeysekera et al. 2011; Ch. 17: Southeast), Northwest (Payne et al. 2004; Vano et al. 2010a; Vano et al. 2010b), Great Plains (Brikowski 2008), and Great Lakes (International Upper Great Lakes Study Board 2012). A number of these assessments demonstrate that while expanding supplies and storage may still be possible in some regions, effective climate adaptation strategies can benefit from: demand management; more flexible, risk-based, better-informed, and adaptive operating rules; and combined surface and groundwater resources management (Brekke et al. 2009b; Georgakakos et al. 2007; Means et al. 2010a; NRC 2011a; Vicuna et al. 2010). Water management and planning would benefit from better coordination between the national, state, and local levels, with participation of all relevant stakeholders in well-informed, fair, and equitable decision-making processes.

Spotlight on Water Management

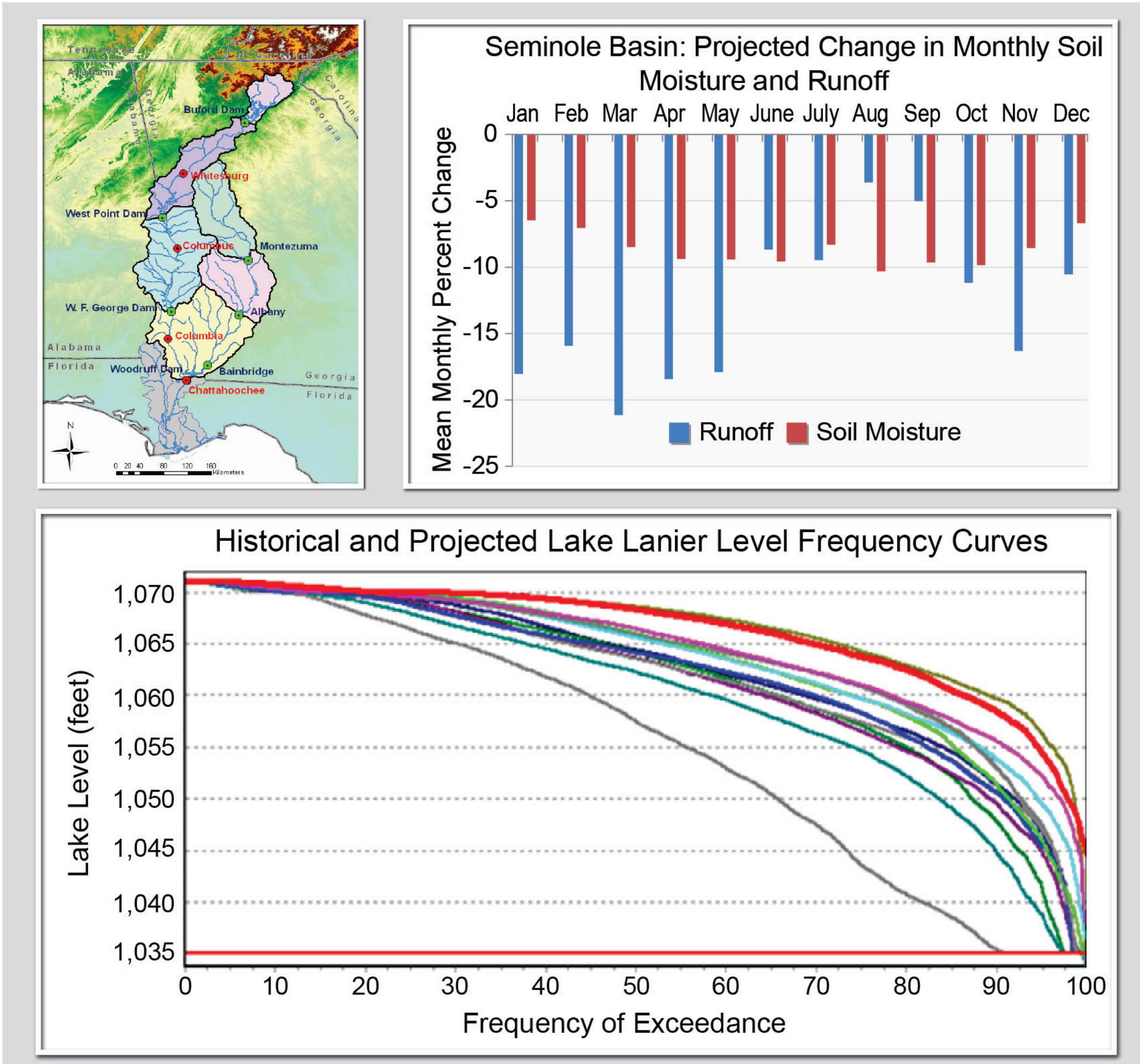

Figure 3.8: Water Challenges in a Southeast River Basin

Caption: The Apalachicola-Chattahoochee-Flint (ACF) River Basin faces several climate-related challenges. **Top:** Comparison of monthly simulated soil moisture and runoff for 50 historical (1960-2009) and future years (2050-2099) based on a scenario of continued increases in emissions (A2) for the Seminole sub-basin of the ACF Basin in the southeastern U.S. Mean soil moisture is projected to decline in all months (droughts), especially during the crop growing season from April to October. Mean runoff declines are also projected throughout the year and especially from November to May. Runoff is projected to exhibit higher wet extremes and flooding risks (not shown). Similar findings apply to all other ACF sub-basins. **Bottom:** Historical (1960-2010; thick red line) and projected Lake Lanier levels under the A2 emission scenario and projected water demands (2050-2099). The frequency curve comparison shows that future lake levels are projected to be lower (by as much as 15 feet) than historical levels throughout the frequency range, particularly during droughts. Figure provided by A. Georgakakis.

Adaptation and Institutional Responses

Increasing resilience and enhancing adaptive capacity are useful strategies for water resources management and planning in the face of climate change. Challenges include: competing demands for water; a variety of institutional constraints; lack of scientific information or access to it; considerable scientific and economic uncertainties; inadequate information useful for practical applications; and difficulties in engaging stakeholders.

Climate change will stress the nation's aging water infrastructure to varying degrees by location and over time. Current drainage infrastructure may be overwhelmed during heavy precipitation and high runoff events anticipated as a result of climate change. Large percentage increases in combined sewage overflow volumes, associated with increased intensity of precipitation events, have been projected for selected watersheds by the end of this century in the absence of adaptive measures (Nilsen et al. 2011; Wilbanks et al. 2012). Infrastructure planning can be improved by incorporating climate change as a factor in new design standards and in asset management and rehabilitation of critical and aging facilities, emphasizing flexibility, redundancy, and resiliency (Brekke et al. 2009a; Means et al. 2010b; Wilbanks et al. 2012).

Adaptation strategies for water infrastructure may include elements of structural *and* non-structural approaches (for example, instituting operational and/or demand management changes) that focus on both adapting physical structures and innovative management (Brekke et al. 2009a; Brown 2010; Wilbanks et al. 2012). Such strategies could take advantage of conventional ("gray") infrastructure upgrades, adjustments to reservoir operating rules, new demand management strategies, land-use management that enhances adaptive capacity, increased reliance on benefits achieved through ecosystem restoration and watershed management, hybrid strategies that blend "green" infrastructure with gray infrastructure, and pricing strategies (Bales et al. 2012; Brekke et al. 2009a; Solecki and Rosenzweig 2012; Wilbanks et al. 2012; Wilby and Keenan 2012).

In addition to physical adaptation, capacity-building activities can build knowledge and enhance communication and collaboration within and across sectors (Bales et al. 2012; Liverman et al. 2012; Wilby and Keenan 2012). In particular, building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Lackstrom et al. 2012; Ch. 26: Decision Support; Ch. 28: Adaptation).

Just as climate change may stress the physical infrastructure of water systems, it also may challenge water laws that are based on an assumption of unchanging regimes of stream flows, water levels, water temperature, or water quality. Existing laws, policies, and regulations, and their current implementation, may limit water management capacity in the context of novel and dynamic conditions (Berry 2012; Brekke et al. 2009a).

The basic paradigms of environmental and natural resources law are preservation and restoration, both of which are based on the assumption that natural systems fluctuate within an unchanging envelope of variability ("stationarity") (Craig 2010). However, climate change is now projected to affect water supplies during the multi-decade lifetime of major water infrastructure projects in wide-ranging and pervasive ways (Brekke et al. 2009a). As a result, stationarity is no longer reliable as the central assumption in water-resource risk assessment and planning (Craig 2010). Instead, a new paradigm that provides additional flexibility in institutional and legal processes will need to be developed, rather than relying on one that narrowly optimizes the distribution of water based on historical experience (Craig 2010).

In the past few years, many federal, state, and local agencies have begun to address climate change adaptation, including it in existing decision-making, planning, or infrastructure-improvement processes (Adelsman and Ekrem 2012; NOAA 2011; State of Oregon 2010; U.S. Bureau of Reclamation 2011b; Ch. 28: Adaptation). Water utilities are increasingly utilizing climate information to prepare assessments of their supplies (EPA 2010), and utility associations and alliances, such as the Water Utility Climate Alliance, have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the U.S. (Barsugli et al. 2009; Carpenter 2011; EPA 2011; Means et al. 2010a).

The economic, social, and environmental implications of climate change-induced water cycle changes are very significant, as is the cost of inaction. Adaptation responses will need to: address considerable uncertainties in the short-, medium-, and long-term; be proactive, integrated, and iterative; and be developed through well-informed stakeholder decision processes functioning within a flexible institutional and legal environment.

Traceable Accounts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: The chapter author team engaged in multiple technical discussions via teleconferences from March – June 2012. These discussions followed a thorough review of the literature, which included an inter-agency prepared foundational document (Bales et al. 2012), over 500 technical inputs provided by the public, as well as other published literature. The author team met in Seattle, Washington in May, 2012 for expert deliberation of draft key messages by the authors wherein each message was defended before the entire author team before this key message was selected for inclusion in the Chapter; these discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities." Key messages were further refined following input from the NCADAC report integration team and authors of Ch. 2: Our Changing Climate.

Key message #1/10	**Annual precipitation and runoff increases are observed now in the Midwest and Northeast regions and are projected to continue or develop in northern states; decreases are observed and projected in southern states.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales. et al, 2012), Ch. 2: Our Changing Climate and Ch. 20: Southwest (2013), (Bales et al. 2012; Garfin et al. 2012; Kunkel et al. 2012a) Garfin et al, 2012, Kunkel et al, 2012, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe precipitation and runoff trends (Diaz et al. 2005; Garfin et al. 2012; Georgakakos and Zhang 2011); see Ch. 2: Our Changing Climate. Notably, the broad trends described in this message and in Ch. 2: Our Changing Climate and Ch. 20: Southwest are trends that are shared by the majority of projections by available climate models and projections (Orlowsky and Seneviratne 2012), lending confidence that the projected precipitation responses (trends) to increasing greenhouse gases are robust in a wide variety of models and depictions of climate at the geographic scale described. There are also many long-term NWS/NCDC weather monitoring networks, USGS streamflow monitoring networks, and analyses of records therefrom, most recently for precipitation as part of NCDC (2011) report and Ch. 2: Our Changing Climate and numerous studies including McCabe and Wolock (2011), Georgakakos & Zhang (2011), and Luce and Holden (2009), that have identified these broad observed trends in precipitation and runoff increases. Projections by ensembles of climate models, reported by Milly et al. (2008), Orlowsky & Seneviratne (2012), and Ch. 2: Our Changing Climate and Ch. 20: Southwest (2013), and Garfin et al. (2012), are basis for the reported projections of trends.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior National Climate Assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/saps). **Observed trends:** Precipitation trends are generally embedded amidst large year-to-year natural variations and thus trends may be difficult to detect, may differ from site to site, and may be reflections of multi-decadal variations rather than external (human) forcings. Consequently, careful analyses of longest-term records from many stations across the country and addressing multiple potential explanations are required and are cornerstones of the evidentiary studies described above. Efforts are underway to continually improve the stability, placement, and numbers of

	weather observations needed to document trends; scientists also regularly search for other previously unanalyzed data sources for use in testing these findings. **Projected trends:** The complexity of physical processes that result in precipitation and runoff reduces abilities to represent or predict them as accurately as would be desired and with the spatial and temporal resolution required for many applications; however, as noted, the trends at the scale depicted in this message are extremely robust among a wide variety of climate models and projections, which lends confidence that the projections are appropriate lessons from current climate (and streamflow) models. Nonetheless, other influences not included in the climate-change projections might influence future patterns of precipitation and runoff, including changes in land cover, water use (by humans and vegetation) and streamflow management. Climate models used to make projections of future trends are continually increasing in number, resolution, and in number of additional external and internal influences that might be confounding current projections (for example, much more of all three of these directions for improvement are already evident in projection archives for the next IPCC assessment).
Assessment of confidence based on evidence	Observed trends have been demonstrated by a broad range of methods over the past 20+ years based on best available data; projected precipitation and runoff responses to greenhouse-gas increases are robust across large majorities of available climate (and hydrologic) models from scientific teams around the world. Confidence is therefore judged to be **high** that precipitation and runoff increases will continue in northern states with increasing fractions of precipitation falling as rain than snow. Confidence is therefore judged to be **high** that precipitation and runoff decreases will continue in southern states.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #2/10	**Summer droughts are expected to intensify in most regions of the U.S., with longer term reductions in water availability in the Southwest, Southeast, and Hawai'i in response to both rising temperatures and changes in precipitation.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.,(2012), Garfin et al., (2012), Ch. 16: Northeast, Ch 17: Southeast and Caribbean, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch, 20 Southwest, Ch. 21: Northwest, and Ch. 23: Hawaii and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. Projected drought trends derive directly from climate models in some studies (e.g., Wehner et al. (2011), from hydrologic models responding to projected climate trends in others (e.g., Reclamation, (2011c); Cayan et al (2010)), from considerations of the interactions between precipitation deficits and either warmer or cooler temperatures in historical (observed) droughts (Cayan et al. 2010) and from combinations of these approaches (for example, (Trenberth et al. 2004; Trenberth and Dai 2007)) in still other studies.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior National Climate Assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/saps). Warmer temperatures, especially in summer and in interior parts of North America, are robustly projected by essentially all climate models, with what are generally expected to be directly attendant increases in the potentials for greater evapotranspiration, or ET (although it is possible that current estimates of future ET are overly influenced by temperatures at the expense of other climate variables, like wind speed, humidity, and net surface radiation, that might change in ways that could partly ameliorate rising ET demands). As a consequence, there is a widespread expectation that more water from precipitation will be evaporated or transpired in the warmer future, so that except in regions where precipitation increases more than ET potential increases, less overall water will remain on the landscape and droughts will intensify and become more common
Assessment of confidence based on evidence	The expectation of future intensification of droughts is supported strongly in the southern regions by a strong consensus of existing climate models towards less precipitation, along with the expectation that ET demands will increase nearly everywhere with rising temperatures. In the northern regions, uncertainties regarding the eventual balance between increased ET demands and increased precipitation (discussed previously), leads to the greatest reductions in confidence in the expectation of more intense drought regimes (although there is still confidence about increasing drought conditions in the summer). Other uncertainties derive from the possibility that changes in other variables or influences of CO_2-fertilization may also partly ameliorate drought intensification. Furthermore in many parts of the country, El Nino-Southern Oscillation (and other oceanic) influences on droughts and floods are large, and can overwhelm climate-change effects during the next few decades. At present, however, the future of these oceanic climate influences remains uncertain. Confidence in the expectation of future intensification of droughts is therefore judged to be **medium-high** except in the Southwest and the lower Great Plains where it is

	high.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #3/10	**Floods are projected to intensify in most regions of the U.S., even in areas where average annual precipitation is projected to decline, but especially in areas are expected to be wetter, such as the Midwest and the Northeast.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.(2012), Garfin et al.(2012), Ch. 16: Northeast, Ch 17: Southeast and Caribbean, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch, 20 Southwest, Ch. 21: Northwest, and Ch. 23: Hawaii and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. Annual peak-flow records from 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes (from the USGS HCDN network), with more than 85 years of records, were the basis for careful national-scale flood-trend analysis by Hirsch & Rhyberg (2012), which provide the principal observational basis for the flood message. Projections of future flood-frequency changes result from detailed hydrologic (for example (Walker et al. 2011); Das et al. (2012); Raff et al. (2009)) models of rivers that simulate responses to projected precipitation and temperature changes from climate models; such simulations have only recently begun to emerge in the peer-reviewed literature.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior National Climate Assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/saps). Large uncertainties still exist as to how well climate models can represent and project future extremes of precipitation, which has—until recently—limited attempts to be specific about future flood frequencies by using climate-model outputs directly or as direct inputs to hydrologic models. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall this results in increased flood potential; furthermore occasional rain-on-snow events exacerbates this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments. Rising sea levels and potentials for intensification of tropical storms and hurricanes provide first-principles bases for expecting intensified flood regimes in Florida and other Southeastern coastal settings (see Ch. 2: Our Changing Climate).
Assessment of confidence based on evidence	Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences, and the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, upstream managements). Consequently, flood frequency changes may not be simple nor regionally homogeneous, and basin by basin projections may need to be developed. Nonetheless, the early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and increasingly rainy (rather than snowy) storms in previously snow-dominated settings. Confidence in current estimates of future changes in flood frequencies and intensities is therefore judged to be **medium**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #4/10	**Expected changes in precipitation and land use in aquifer recharge areas, combined with changes in demand for groundwater over time, will affect groundwater supplies in ways that are not well monitored or understood.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.(2012), Garfin et al.(2012), NCA regional chapters (2013), and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. For many aquifers in the Southwest region, there is a growing literature of geochemical studies that fingerprint various properties of groundwater and that are demonstrating that most western groundwater derives preferentially from snowmelt, rather than rainfall or other sources (Earman and Phillips 2003; Earman et al. 2006; Liu et al. 2004; Manning and Solomon 2003; Manning et al. 2012; Phillips et al. 2004; Rademacher et al. 2002; Rose et al. 2003); this finding suggests that much western recharge may be at risk of changes and disruptions from projected losses of snowpack, but as yet provides relatively little indication whether the net effects will be recharge declines, increases, and simply spatial redistribution.
New information and remaining uncertainties	The observations and, even, modeling evidence for making projections of future responses of groundwater recharge and discharge to long-term climate changes are thus far very limited, primarily because of limitations in data availability and in the models themselves. Additional monitoring and modeling studies of the responses of groundwater recharge and discharge to climate change are needed to increase confidence. Despite the low confidence about the specifics of climate change impacts on groundwater, impacts of reduced groundwater supply and quality would likely be detrimental to the nation.
Assessment of confidence based on evidence	New forms and networks of observations, and new modeling approaches and tools, are needed to provide projections of the likely influences of climate changes on groundwater systems. The nature of these changes, however, remains unexplored. Confidence is therefore judged to be **high** that groundwater aquifers will be influenced by climate change at aquifer recharge areas and by increased groundwater use in ways that remain unexplored.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #5/10	**Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to challenge the sustainability of coastal freshwater aquifers and wetlands.**
Description of evidence base	Considerable historical experience with seawater intrusion into many of the Nation's coastal aquifers under the influence of heavy pumpage, some experience with the influences of droughts and some storms on seawater intrusion in at least some coastal aquifers, and experience with seepage of seawater into shallow coastal aquifers under storm and storm surges conditions that lead to coastal inundations with seawater provide a strong basis for both practical, and theoretical, expectations expressed by this message. The likely influences of sea level rise on seawater intrusion into coastal (and island) aquifers are somewhat less certain, as discussed below, although it is often assumed that sea level rise may increase tendencies for higher sea levels to increase opportunities for saltwater intrusion (see Ch. 25: Coastal Zone).
New information and remaining uncertainties	Chang et al. (2011) have recently provided theoretical and modeling arguments that sea level rise need not generally induce significantly greater seawater intrusion unless freshwater recharge and discharge also change. In essence, Chang et al. (2011) show that the lens of freshwater in coastal aquifers may essentially float atop the rising saline waters in ways that preserve the lens and prevent significant intrusion, unless the water balance of the freshwater lens is altered by changing recharge and/or water use patterns. Other than the findings of Chang et al. (2011), there are few published studies describing the kinds of groundwater quality and flow modeling that are necessary to assess the real-world potentials for sea level rise to affect seawater intrusion. Studies in the literature and historical experience demonstrate the detrimental impacts of alterations to the water budgets of the freshwater lenses in coastal aquifers (most often, by groundwater development) around the world, but few evaluate the impacts of sea level rise alone. More studies with real-world aquifer geometries and development regimes are needed to reduce the current uncertainty of the potential interactions of sea level rise and seawater intrusion.
Assessment of confidence based on evidence	Confidence is **high** that sea level rise, intensifying storms and larger storm surges may challenge the sustainability of coastal freshwater aquifers and wetlands (see Ch. 25: Coastal Zone).

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #6/10	**Air and water temperatures, precipitation intensity, and droughts affect water quality in rivers and lakes. More intense runoff and precipitation generally increase river sediment, nitrogen, and pollutant loads. Increasing water temperatures and intensifying droughts can decrease lake mixing, reduce oxygen in bottom waters, and increase the length of time pollutants remain in water bodies.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.,(2012), Ch. 8: Ecosystems and Biodiversity, Ch. 15: Biogeochemical Cycles, and over 500 technical inputs on a wide range of topics that were reviewed as part of the Federal Register Notice solicitation for public input. Thermal stratification of deep lakes and reservoirs has been observed to increase with increased air and water temperatures (Bales et al. 2012; Coats et al. 2006; Sahoo and Schladow 2008; Sahoo et al. 2011; Schneider and Hook 2010), and may be eliminated in shallow lakes. Increased stratification reduces mixing, resulting in reduced oxygen in bottom waters. Oxygen solubility decreases as temperature increases (Wetzel 2001). Deeper set-up of vertical thermal stratification in lakes and reservoirs may reduce or eliminate a bottom cold water zone; this coupled with lower oxygen concentration result in a degraded aquatic ecosystem. Major precipitation events and resultant water flows increase watershed pollutant scour and thus increase pollutant loads. Models predict and observations confirm that continued warming will have increasingly negative effects on lake water quality and ecosystem health (Sahoo and Schladow 2008; Sahoo et al. 2011). Although not yet observed, warming lake water has the potential to cross important temperature thresholds, allowing invasion by non-native species. In the Mississippi drainage basin, increased precipitation has resulted in increased nitrogen loads contributing to hypoxia in the Gulf of Mexico (Justic et al. 2005; McIsaac et al. 2002). Fluxes of mineral weathering products (e.g., Ca, Mg, Na, and Si) have also been shown to increase in response to higher discharge (Godsey et al. 2009). Future re-mobilization of sediment stored in large river basins will be influenced by changes in flood frequencies and magnitudes, as well as on vegetation changes in the context of climate and other anthropogenic factors (Osterkamp and Hupp 2010). Model projections suggest that changes in sediment delivery will vary regionally and by land-use type, but on average could increase by 25% to 55% (Nearing et al. 2005).
New information and remaining uncertainties	It is unclear whether increasing floods and droughts cancel each other out with respect to long term pollutant loads. It is also uncertain whether the absolute temperature differential with depth will remain constant, even with overall lake/reservoir water temperature increases; further, it is uncertain if greater mixing with depth will eliminate thermal stratification in shallow, previously stratified lakes. Although recent studies of Lake Tahoe provide an example of this, other lakes in other settings and with other geometries may not exhibit the same response. Many factors influence stream water temperature, including air temperature, forest canopy cover, and ratio of baseflow to streamflow. However, projected declines in

	summer flows mean that there will be less water to heat in the months when the water is warmest (Cayan et al. 2001; Leppi et al. 2011).
Assessment of confidence based on evidence	Based on the evidence base: 1) Confidence is **very high** that lake temperatures will increase and dissolved oxygen will decrease due to climate change. Confidence is **very high** that temperatures will increase and dissolved oxygen will decline in many streams; however, place to place (among streams and along streams) differences are likely. 2) Confidence is **high** there will be decreases in mixing in some lakes and reservoirs due to climate change. 3) Confidence is **medium** that sediment, nitrogen, and pollutant loads will increase due to climate change.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #7/10	**In the Southwest, parts of the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai'i, surface and groundwater supplies are already affected and expected to be reduced by declining runoff and groundwater recharge trends, increasing the likelihood of water shortages for many off-stream and in-stream water uses.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document, Bales. et al. (2012), Ch. 2: Our Changing Climate, Ch. 17: Southeast and Caribbean, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawaii and Pacific Islands (2013), Garfin et al. (2012), and over 500 technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input. **Observed Trends:** Observations suggest that the water cycle in the Southwest, Great Plains, and Southeast U.S. has been changing toward dryer conditions (Barnett and Pierce 2009; Georgakakos et al. 2010; Hirsch and Ryberg 2012; Rajagopalan et al. 2009; Ch. 17: Southeast). Furthermore, paleo-climate tree-ring reconstructions indicate that drought in previous centuries has been more intense and of longer duration than the most extreme drought of the 20th and 21st centuries (Meko et al. 2007). **Projected Trends and Consequences:** GCM projections indicate that this trend is likely to persist, with runoff reductions in the range 10-20% over the next 50 years, and intensifying droughts (Cayan et al. 2010). The drying water cycle is expected to affect all human and ecological water uses, especially in the Southwest. This region extends over six states (Colorado, New Mexico, Utah, Arizona, Nevada, and California) and is inhabited by more than 60 million people. Decreasing precipitation, rising temperatures, and drying soils are projected to increase irrigation and outdoor watering demand (which account for nearly 90% of consumptive water use) by as much as 35% by 2060 under the A2 climate scenario (Foti et al. 2012). Decreasing runoff and groundwater recharge are expected to reduce surface and groundwater supplies (Earman and Dettinger 2011), increasing the annual risk of water shortages from 25 to 50% by 2060 (Rajagopalan et al. 2009). Changes in streamflow timing will increase the mismatch of supply and demand. Earlier and declining streamflow and rising demands will make it more difficult to manage reservoirs, aquifers, and other water infrastructure (Rajagopalan et al. 2009). Rising water temperatures and longer low flow periods may make thermoelectric water withdrawals unreliable, and aquatic and riparian ecosystems susceptible to degraded habitats and invasive, non-native species (Backlund et al. 2008). Such impacts and consequences have been identified for several Southwest river basins including the Colorado (U.S. Bureau of Reclamation 2011c), Rio Grande (Ward et al. 2006), and Sacramento-San Joaquin (Brekke et al. 2009b; Connell-Buck et al. 2012; Georgakakos et al. 2012).
New information and remaining uncertainties	The drying climate trend observed in southern California, Southwest, and Southeast in the last decades is consistent across all water cycle variables (precipitation, temperature, snow cover, runoff, streamflow, reservoir levels, and soil moisture) and is not debatable. The debate is over whether this trend is part of a multi-decadal climate cycle, and, at some future time, it will reverse direction. However, the rate of change and the comparative GCM assessment results with and without historical

	CO_2 forcing (Ch. 2: Our Changing Climate) support the view that the observed trends are due to both factors acting concurrently. GCMs continue to be uncertain with respect to precipitation, but they are very consistent with respect to temperature. Runoff, streamflow, and soil moisture depend on both variables and are thus less susceptible to GCM precipitation uncertainty. The observed trends and the general GCM agreement that the southern states will continue to experience streamflow and soil moisture reductions(Georgakakos and Zhang 2011; U.S. Bureau of Reclamation 2011a) provides confidence that these projections are robust.
Assessment of confidence based on evidence	Confidence is **high** that in the Southwest, the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai‘i, surface and groundwater supplies will be affected by declining runoff and uncertain groundwater recharge changes, increasing the risk of water shortages for many groundwater, off-stream, and in-stream water uses.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #8/10	**Increasing flooding risk affects human safety and health, property, infrastructure, economy, and ecology in many basins across the U.S.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales. et al, 2012), the the chapters Our Changing Climate, Northwest, Great Plains, Midwest, Northeast and multiple others (2013), and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. **Observed Trends:** Annual peak-flow records from 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes (from the USGS HCDN network), with more than 85 years of records, were the basis for careful national-scale flood-trend analysis (Hirsch and Ryberg 2012), providing the observational basis for this message. Additional observational evidence that heavy precipitation events are increasing in the northern states can be found in Ch. 2: Our Changing Climate. **Projected Trends:** Projections of future flood-frequency changes result from detailed hydrologic (Das et al. 2012; Raff et al. 2009; Walker et al. 2011) and hydraulic models of rivers that simulate responses to projected precipitation and temperature changes from climate models. **Consequences:** Floods already impact human health and safety and result in substantial economic, ecological, and infrastructure damages. Many cities are located along coasts and, in some of these cities including New York, Boston, Miami, Savannah, and New Orleans, sea level rise is expected to exacerbate coastal flooding issues by backing up flood flows and impeding flood-management responses (see Ch. 16: Northeast and Ch. 25: Coastal Zone). Projected changes in flood frequency and severity can bring new challenges in flood risk management. For urban areas in particular, flooding impacts critical infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (for example, failure of electrical generating lines can cause pump failure, additional flooding, and failure of evacuation services). Increasing likelihood of flooding also brings with it human health risks associated with failure of critical infrastructure (Ebi et al. 2006; Kessler 2011; Patz et al. 2000; Wright et al. 2012) (see Ch. 11 Urban and Infrastructure), from waterborne disease that can persist well beyond the occurrence of extreme precipitation (Curriero et al. 2001) (see Ch. 9: Human Health), from water outages associated with infrastructure failures that cause decreased sanitary conditions (Huang et al. 2011), and also from ecosystem changes that can affect airborne diseases (Ziska et al. 2008; Ch. 8: Ecosystems and Biodiversity).
New information and remaining uncertainties	Large uncertainties still exist as to how well climate models can represent and project future precipitation extremes. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall this results in increased flood potential; furthermore occasional rain-on-snow events exacerbates this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.

Assessment of confidence based on evidence	Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences, and the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, upstream managements). Consequently, flood frequency changes may not be simple nor regionally homogeneous, and basin by basin projections may need to be developed. Nonetheless, early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and more rainfall runoff from previously snowbound catchments and settings. Therefore confidence is judged to be **medium** that flooding risk will increase, potentially affecting human safety and health, property, infrastructure, economy, and ecology in most regions across the U.S.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #9/10	**In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales et al. 2012), NCA chapters (2013), and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. **Observed and Projected Trends:** Many U.S. regions are facing critical water management and planning challenges. South Florida's groundwater supplies, ecology, and coastal communities are becoming increasingly vulnerable to sea level rise and drought impacts, but many GCMs cannot capture the regional climate trends (Obeysekera et al. 2011). The Sacramento – San Joaquin Bay Delta is already threatened by flooding, sea water intrusion, and changing needs for environmental, municipal, and agricultural water uses. Managing these risks and uses requires re-assessment of a very complex system of water rights, levees, stakeholder consensus processes, reservoir system operations, and significant investments, all of which are subject to large uncertainties (NRC 2010, 2011b, 2012). Given the projected climate changes in this area (Cayan et al. 2008; Cloern et al. 2011), adherence to historical management and planning practices may not be a long-term viable option (Brekke et al. 2009b; Georgakakos et al. 2012), but the supporting science is not yet fully actionable (Milly et al. 2008), and a flexible legal and policy framework embracing change and uncertainty is lacking. The Apalachicola-Chattahoochee-Flint (ACF) River basin in Georgia, Alabama, and Florida supports a wide range of water uses and the regional economy, but it has been fraught by litigious conflicts for more than 20 years. An inclusive stakeholder coalition offers new hope that a shared vision plan may still be formulated, but climate change presents new stresses and uncertainties (Georgakakos et al. 2010). Intense water management challenges have also been reported in the Southwest (Barnett and Pierce 2009; Rajagopalan et al. 2009), Northwest (Vano et al. 2010a; Vano et al. 2010b), Great Plains, and Great Lakes (International Upper Great Lakes Study Board 2012).
New information and remaining uncertainties	Climate, demand, land use, and demographic changes combine to challenge water management in unprecedented ways. This is happening with a very high degree of certainty in most U.S. regions. Regardless of its underlying causes, climate change poses difficult challenges for water management because it invalidates stationarity – the perception that climate varies around a predictable mean based on the experience of the last century - and increases hydrologic variability and uncertainty. These conditions suggest that past management practices will become increasingly ineffective and that water management can benefit by the adoption of iterative, risk-based, and adaptive approaches.
Assessment of confidence based on evidence	The water resources literature is unanimous that water management should rely less on historical practices and responses and more on robust, risk-based, and adaptive decision approaches. Therefore confidence is **very high** that in most U.S. regions, water resources managers and planners will face new risks, benefits, and vulnerabilities that may not be properly managed with existing practices.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #10/10	**Increasing resilience and enhancing adaptive capacity are useful strategies for water resources management and planning in the face of climate change. Challenges include: competing demands for water; a variety of institutional constraints; lack of scientific information or access to it; considerable scientific and economic uncertainties; inadequate information useful for practical applications; and difficulties in engaging stakeholders.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales et al. 2012), Garfin et al.(2012), and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input. The key message is a restatement of conclusions derived from the peer-reviewed literature as cited in the reference list for the chapter. The two parts of the key message are described separately below. Increasing resilience and adaptive capacity is a crucial and low-regrets strategy for water resources management and planning in the face of climate change. Water utilities appear to be benefiting from various efforts to assess their potential vulnerabilities and long term planning options for responding to climate change (EPA 2010). Building human and social capital through networks and partnerships is identified as both major assets and continued needs; building networks of colleagues is identified as important sources of accessible, relevant and trusted information (Lackstrom et al. 2012). Building adaptive capacity ultimately increases the ability to develop and implement adaptation strategies and is considered a no-regrets strategy (Bales et al. 2012). A very useful strategy for risk management in an uncertain future "is to build the capacity to address climate change impacts in the future, including improving understanding of the problem, educating and building awareness among citizens, establishing collaborative ties with others, improving data sharing and communication, setting up stakeholder engagement processes, and developing funding mechanism" (Liverman et al. 2012). Challenges include competing water uses; considerable uncertainties; insufficient actionable science ready for practical application; the challenges of stakeholder engagement; and a lack of agreement on alternative paradigms to "post-stationarity" on which to base water laws, regulations, and policies. Additional support for this part of this key message is as follows: Climate change will stress the current state-based water allocation systems and create new conflicts between consumptive and non-consumptive, especially environmental, uses (Tarlock 2010). With a very few exceptions, water users have no right to take water other than in accordance with state law. Laws differ from the East's riparianism and regulated riparianism, to the West's prior appropriation doctrines, with differing ability to accommodate the stress of climate change (Adler 2010; Hall and Abrams 2010). Adaptation management will have to cope with many layers of government, because many adaptation problems and strategies will be local in implementation while

	adaptation principles and goals may arise and be organized at larger state, watershed, regional or national scales. Key principles suggested for adaption legal regimes are to: 1) increase monitoring and study; 2) eliminate or reduce non-climate change stress and promote resilience; 3) encompasses immediate, "no regrets" changes; 4) plan for the long term increased coordination across media, sectors, interests, and governments; 5) promote principled flexibility in regulatory goals and natural resource management, and 6) accept that adaptation may require loss (Craig 2010). There are many examples of federal, state and local adaptation efforts including interstate institutions (Hall and Abrams 2010), regionalization of supplies (Heimlich et al. 2009), adaptive management of existing supply systems (Short et al. 2012; Solecki and Rosenzweig 2012), decision support planning methods (Adams et al. 2012), initiatives to balance instream and off stream benefits (Hall and Abrams 2010; Tarlock 2010; U.S. Bureau of Reclamation 2012; Washington State Department of Ecology 2011) and innovative international engagement with Mexico (IBWC 2010; Megdal and Scott 2011; Transboundary Aquifer Assessment Act 2009; Vickery 2009; Wilder et al. 2012). (see Ch. 28: Adaptation).
New information and remaining uncertainties	Jurisdictions at the state and local level are addressing climate change related legal and institutional issues on an individual basis. An on-going assessment of these efforts may show more agreement and practical applications.
Assessment of confidence based on evidence	Confidence is **very high** that increasing resilience and adaptive capacity is a useful strategy for water resources management and planning in the face of climate change. Confidence is **very high** that there are challenges to realizing increased resilience and adaptive capacity.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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4. Energy Supply and Use

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Key Messages

1. **Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of extreme weather events are expected to increase.**
2. **Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net energy use is projected to increase as rising demands for cooling outpace declining heating energy demands.**
3. **Both episodic and long-lasting changes in water availability will constrain different forms of energy production.**
4. **In the longer term, sea level rise will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.**
5. **As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways – depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.**

Introduction

The U.S. energy supply system is diverse and robust in its ability to provide a secure supply of energy with only occasional interruptions. However, projected impacts of climate change will amplify seasonal patterns of energy use and affect energy infrastructure, posing additional risks to energy security. Extreme weather events and water shortages are already interrupting energy supply, and impacts are expected to increase in the future. Most vulnerabilities and risks to energy supply and use are unique to local situations; others are national in scope.

The impacts of climate change in other countries will also affect U.S. energy systems through global and regional cross-border markets and policies. Increased energy demand within global markets due to industrialization, population growth, and other factors will influence U.S. energy costs through competition for imported and exported energy products.

Adaptation actions can allow energy infrastructure to adjust more readily to climate change, and many investments toward adaptation provide short-term paybacks because they address current vulnerabilities as well as future risks, and thus, entail "no regrets." Such actions can include a focus on increased efficiency of energy use as well as improvements in the reliability of production and transmission of energy.

Disruptions from Extreme Weather

Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of extreme weather events are expected to increase.

Much of America's energy infrastructure is vulnerable to extreme weather events. Because so many components of U.S. energy supplies – like coal, oil, and electricity – move from one area to another, extreme weather events affecting energy infrastructure in one place can lead to supply consequences elsewhere.

Climate change has begun to affect the frequency, intensity, and length of many extreme weather events (Peterson et al. 2012; Solomon et al. 2007). What is considered an extreme weather or climate event varies from place to place (See Ch. 2: Our Changing Climate). Across the U.S., observed changes include increased frequency and intensity of extreme precipitation events, winter storms, heat waves, and droughts.

Most areas in the U.S. are projected to experience increases in the number of days with precipitation exceeding one inch. It is projected that future climate change will include increases in some types of extreme weather events, particularly heat waves, wildfire, flooding, longer and more intense drought, heavy precipitation in winter storms, and extreme coastal high water due to storm events and sea level rise which will increasingly disrupt infrastructure services in some locations (Wilbanks et al. 2012a). Disruptions in services in one infrastructure system (such as energy) will lead to disruptions in one or more other infrastructures (such as communications and transportation) that depend on other affected systems. Infrastructure that is located in areas exposed to extreme weather, where it is also stressed by age or by demand levels that exceed what it was designed to deliver, is particularly vulnerable (See Ch. 11: Urban and Infrastructure).

Like much of the nation's infrastructure that has been affected by the increasing occurrence of "billion dollar weather events" (NOAA 2011), U.S. energy facilities and systems, especially those located in coastal areas, are vulnerable to extreme weather events. Wind and storm surge damage by hurricanes already causes significant infrastructure losses on the Gulf Coast.

Economic losses arising from weather and climate events are large and have been increasing. Damage to oil and gas production and delivery infrastructure by Hurricanes Katrina and Rita affected natural gas, oil, and electricity markets in most parts of the U.S. (Entergy Corporation 2012; Wilbanks et al. 2012a). Market impacts were felt as far away as New York and New England (Hibbard 2006; Rosenzweig et al. 2009), highlighting the interdependencies among various types of infrastructure that can amplify the vulnerabilities of energy infrastructure alone to climate-related impacts.

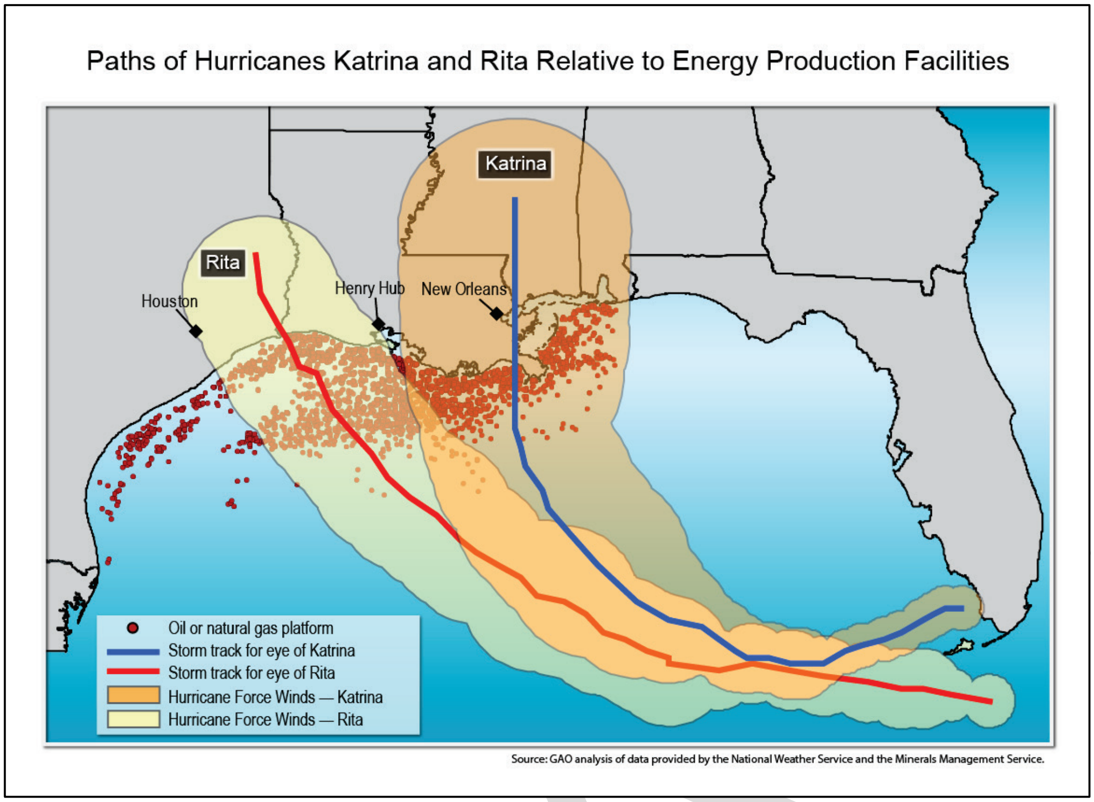

Figure 4.1: Paths of Hurricanes Katrina and Rita Relative to Energy Production Facilities

Caption: A substantial portion of U.S. energy facilities are located on the Gulf Coast as well as offshore in the Gulf of Mexico, where they are particularly vulnerable to hurricanes and other storms and sea level rise. (Source: Wilbanks et al. 2012a).

Various aspects of climate change will affect energy systems. It is projected that wildfires will affect extensive portions of California's electricity transmission grid (Sathaye et al. 2011). Extreme surge events at high tides are expected to increase (Cayan et al. 2003), raising the risk of inundating energy facilities such as power plants, refineries and pipelines. Rail transportation lines that carry coal to power plants, which produced 42% of U.S. electricity in 2011, often follow riverbeds, especially in the Appalachian region. More intense rainstorms, both observed and projected, can lead to river flooding that degrades or washes out nearby railroads and roadbeds.

Climate Change and Seasonal Energy Demands

Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net energy use is projected to increase as rising demands for cooling outpace declining heating energy demands.

Over the last 20 years, annual average temperatures typically have been higher than the long-term average; nationally, temperatures were above average during 12 of the last 14 summers (Kunkel et al. 2012a; Ch. 2: Our Changing Climate). These increased temperatures are already affecting the demand for energy needed to cool buildings within the U.S.

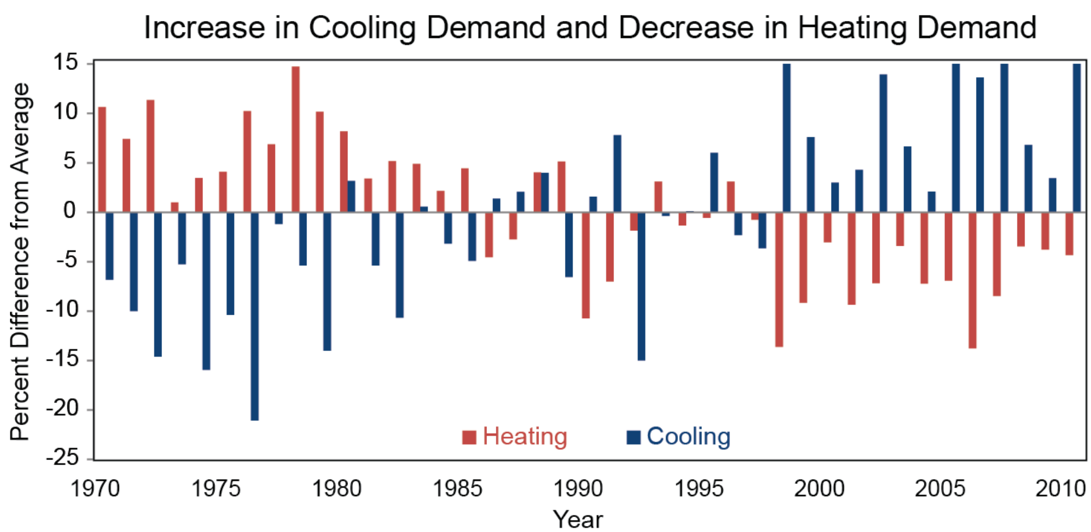

Figure 4.2: Increase in Cooling Demand and Decrease in Heating Demand

Caption: The amount of energy needed to cool (or warm) buildings is proportional to cooling (or heating) degree days. The figure shows increases in "cooling degree days," which result in increased air conditioning use, and decreases in "heating degree days," meaning less energy required to heat buildings in winter, compared to the average for 1970-2000. Cooling degree days are defined as the number of degrees that a day's average temperature is *above* 65ºF, while heating degree days are the number of degrees a day's temperature is *below* 65ºF. As shown, the increase in cooling needs is greater than the decrease in heating needs (Source: EIA 2008; 2009; U.S. Department of Energy 2012; National Climatic Data Center 2012).

The rate of temperature change has increased in recent decades. In response, the Energy Information Administration began using 10-year average weather data instead of 30-year data in order to estimate energy demands for heating and cooling purposes. The shorter period is more consistent with the observed trend of warmer winters and summers (EIA 2008).

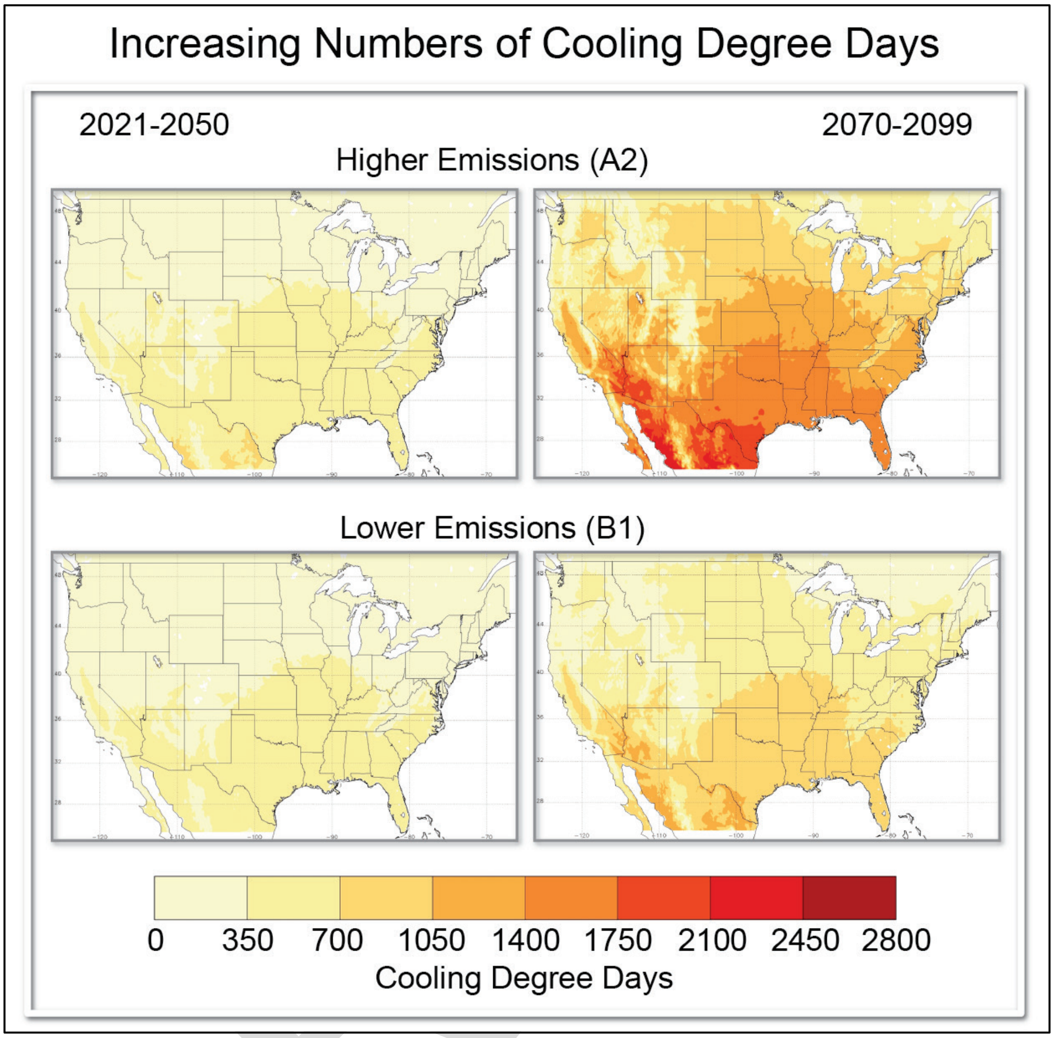

Figure 4.3: Increasing Numbers of Cooling Degree Days

Caption: A recent analysis (Kunkel et al. 2012b) projects continued increases in cooling degree days (and decreases in heating degree days) over the next several decades. The higher the number of cooling degree days, the more people tend to use air conditioning.

These maps show projected average changes in cooling degree days compared to the baseline period (1971-2000) for two periods in the rest of this century (2021-2050 and 2070-2099), assuming climate change associated with continued increases in emissions (A2, top maps) and significant reductions in emissions of heat-trapping gases (B1, bottom maps).

The projections show significant regional variations, with the greatest increases in the southern U.S. By the end of this century, the increases in cooling degree days will be more pronounced for the higher emissions (A2) scenario. Furthermore, projections suggest continued population shifts toward areas that require air conditioning in the summer, thereby increasing the impact of temperature changes on increased energy demand (U.S. Census Bureau 2012). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Statistically Downscaled.)

While recognizing that many factors besides climate change affect energy demand (including population changes, economic conditions, energy prices, consumer behavior, conservation programs, and changes in energy-using equipment), increases in temperature will result in increased energy use for cooling and decreased energy use for heating. These impacts differ among regions of the country and indicate a shift from predominantly heating to predominantly cooling in some regions with moderate climates. For example, in the Pacific Northwest, energy demand for cooling is projected to increase over the next century due to population growth, increased cooling degree days, and increased use of air conditioners as an adaptation response to higher temperatures (Hamlet et al. 2010). Population growth is also expected to increase energy demand for heating. However, the projected increase in energy demand for heating is about half as much when the effects of a warming climate are considered along with population growth (Hamlet et al. 2010).

Table 4.1: Changing Energy Use for Heating and Cooling Will Vary by Region

Region	Consequences: Challenges and Opportunities	
	Electricity Use	Natural Gas (Heating)
Physical Impacts - High Likelihood	**Warmer and longer summers** Number of Additional Extreme Days(> 95°F) and % Increase in Cooling Degree Days in 2041-2070 above 1971-2000 Level	**Warmer winters** Number of Fewer Extreme (< 10°F) Cold Days and % Decrease in Heating Degree Days in 2041-2070 below 1971-2000 Level
Northeast	+ 10 days, +77%	- 12 days, - 17%
Southeast	+23 days, 43%	- 2 days, - 19%
Midwest	+ 33 days, +64%	- 14 days, - 15%
Great Plains	+ 22 days, +37%	- 4 days, -18%
Southwest	+ 20 days, +44%	- 3 days, - 20%
Northwest	+ 5 days, +89%	- 7 days, - 15%
Alaska	Assumed Neutral - Not modeled	Assumed - Not modeled
Pacific Islands	Assumed - Not modeled	Assumed Neutral – Not modeled

Red cells denote negative impacts; green cells denote positive impacts.

Title: Changing Energy Use for Heating and Cooling Will Vary by Region

Caption: Warmer and longer summers will increase the amount of electricity necessary to run air conditioning, especially in the Southeast and Southwest. Warmer winters will decrease the amount of natural gas required to heat buildings, especially in the Northeast, Midwest and Northwest. Table information is adapted from multi-model means from 8 NARCCAP regional climate simulations for the high (A2) emissions scenario considered in this report, (Figure Source: adapted from Kunkel et al. 2012f, 2012g; Kunkel et al. 2012h; Kunkel et al. 2012c; Kunkel et al. 2012d; Kunkel et al. 2012e) weighted by population.

Increases in average temperatures and temperature extremes are expected to lead to increasing demands for electricity for cooling in every U.S. region. Virtually all cooling load is handled by the electrical grid, while the heating load is distributed among electricity, natural gas, heating oil, passive solar, and biofuel. In order to meet increased demands for peak electricity, additional generating and distribution facilities will be needed, or demand will have to be managed through a variety of mechanisms. Electricity at peak demand typically is more expensive to supply than at average demand (Wilbanks et al. 2012b). Because the balance between heating and cooling differs by location, the balance of energy use among delivery forms and fuel types will likely shift – from natural gas and fuel oil used for heating, to electricity used for air conditioning. In hotter conditions, more fuel and energy are required to generate and deliver electricity; so a shift to more air conditioning in regions with moderate climates will increase primary energy demands. Also, because of greater energy losses for generating and delivering energy in hotter conditions, the expected shift (due to climate change) from heating to cooling in regions with moderate climates can increase primary energy demand (Wilbanks et al. 2012a).

Climate-related temperature shifts are expected to cause a net increase in residential energy use. Increased energy demands for cooling exceed energy savings resulting from lower energy demands for heating. One study examining state-level energy consumption, weather data, and high emission scenarios (SRES A1Fi and A2) found a net increase of 11% in residential energy demand (Deschênes and Greenstone 2011). Another study reported annual increases in net energy expenditures for cooling and heating of about 10% ($26 billion in 1990 U.S. dollars) by the end of this century for 4.5°F of warming, and 22% ($57 billion in 1990 dollars) for overall warming of about 9°F (Mansur et al. 2008). New energy efficient technology could help to offset growth in demand.

Several studies suggest that if substantial reductions in emissions of heat-trapping gases were required, the electricity generating sector would decarbonize first, given the multiple options available to generate electricity from sources that do not emit heat-trapping gases, such as wind and solar power. Under these circumstances, electricity would displace direct use of fossil fuels for some applications, such as heating, to reduce overall emissions of heat-trapping gases (Clarke et al. 2007; Wei 2012; Williams et al. 2012). The implications for peak electricity demand could be significant. In California, for example, the estimated increase in use of electricity for space heating would shift the peak in electricity demand from the summer to the winter (Wei 2012).

Implications of Less Water for Energy Production

Both episodic and long-lasting changes in water availability will constrain different forms of energy production.

Producing energy from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems often depends on the availability of adequate and sustainable supplies of water. Issues related to water already pose challenges to production from existing power plants and the permitting of new facilities (Averyt et al. 2011; Wilbanks et al. 2012b; Ch. 10: Water, Energy, and Land Use).

In the future, long-term precipitation changes, drought, and reduced snowpack are projected to alter water availability. Recent climate data indicate an overall upward trend in annual precipitation across most of the nation (Ch. 2: Our Changing Climate). However, the Southwest faces lower precipitation year round. The widespread trend toward more heavy downpours is expected to continue, with precipitation becoming less frequent but more intense. Most of the U.S. is projected to have 15 more days per year with little precipitation.

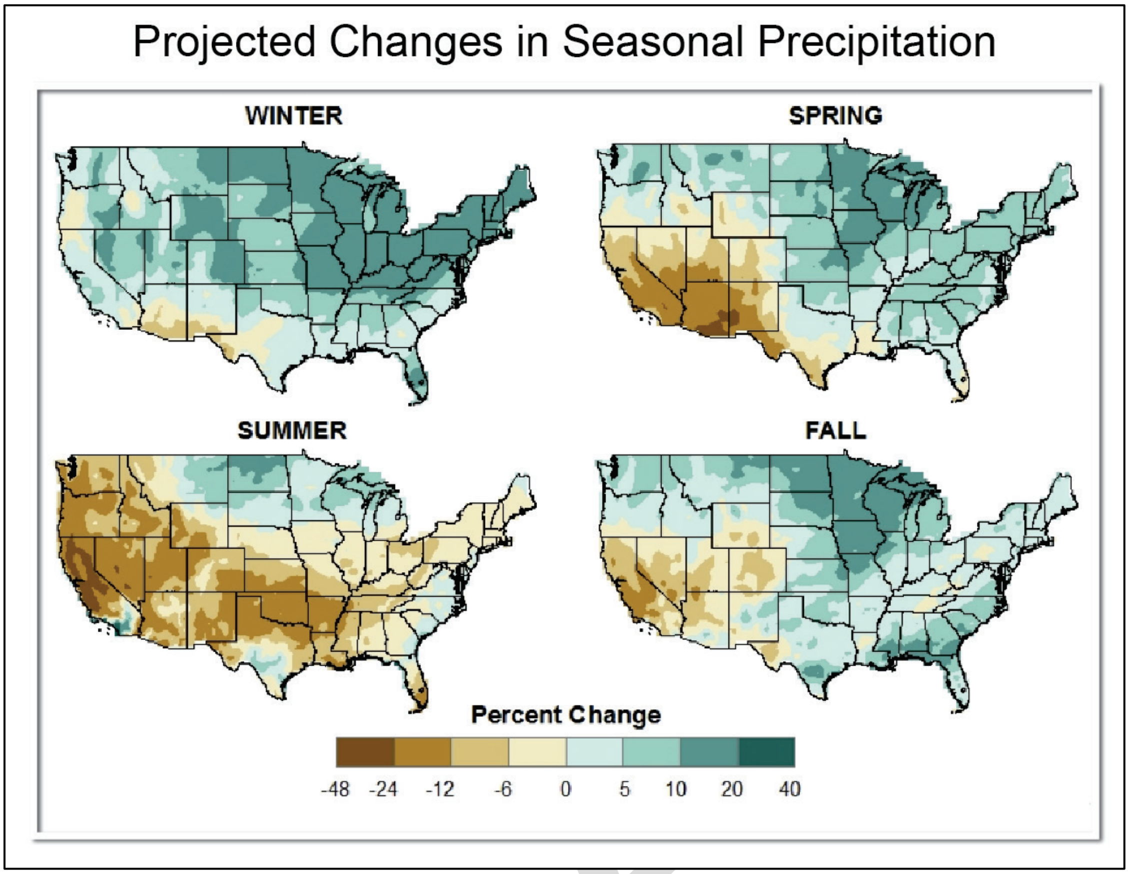

Figure 4.4: Projected Changes in Seasonal Precipitation

Caption: Climate change affects precipitation patterns as well as temperatures. The maps show projected changes (percent) in average precipitation by season for 2041–2070 compared to 1971–2000, assuming emissions of heat-trapping gases continue to rise (A2 scenario). Note significantly drier conditions in the Southwest spring and Northwest summer, as well as significantly more precipitation (some of which could fall as snow) projected for northern states in winter and spring.

(Figure source: NOAA NCDC / CICS-NC. Data from NARCCAP.)

Reduced availability of water for cooling, for hydropower, or for absorbing warm water discharges into water bodies without exceeding temperature limits, will continue to constrain power production at existing facilities and permitting of new power plants. Increases in water temperatures may reduce the efficiency of thermal power plant cooling technologies, potentially leading to warmer water discharge from some power plants, which in turn can affect aquatic biota. Studies conducted during 2012 indicate that water shortages are more likely to limit power plant electricity production in many regions (Skaggs et al. 2012; Wilbanks et al. 2012b). Regional or seasonal water constraints, particularly in the Southwest and Southeast, will result from chronic or seasonal drought, growing populations, and increasing demand for water for various uses (Averyt et al. 2011; Ch. 10: Water, Energy, and Land Use).

Hydropower plants in the West depend on the seasonal cycle of snowmelt to provide steady output throughout the year. Expected reductions in snowpack in parts of the West will reduce hydropower production. There will also be increases in energy (primarily electricity) demand in order to pump water for irrigated agriculture and to pump and treat water for municipal uses. (Wilbanks et al. 2012b).

The Electric Power Research Institute's (EPRI) scenario-based technical projections of water demand in 2030 find that one-quarter of existing power generation facilities (about 240,000 megawatts) nationwide are in counties that face some type of water sustainability (EPRI 2011). Many regions face water sustainability concerns, with the most significant water-related stresses in the Southeast, Southwest, and Great Plains regions.

Sea Level Rise and Infrastructure Damage

In the longer term, sea level rise will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

Significant portions of the Nation's energy production and delivery infrastructure are in low-lying coastal areas; these facilities include oil and natural gas production and delivery facilities, refineries, power plants, and transmission lines.

Global sea level has risen by about 8 inches since reliable record keeping began in 1880, affecting countries throughout the world, including the U.S. The rate of rise increased in recent decades and is not expected to slow. Global average sea level is projected to rise 1 to 4 feet by 2100, though considering potential increases of up to 6.6 feet during this century may be useful for decision makers with a low tolerance for risk (Ch.2: Our Changing Climate). Sea level change at any particular location can deviate substantially from this global average (Parris et al. 2012; Ch. 2: Our Changing Climate) .

Rising sea levels, combined with normal and potentially more intense coastal storms and local land subsidence, threaten coastal energy equipment as a result of inundation, flooding, or erosion. In particular, sea level rise and coastal storms pose a danger to the dense network of Outer Continental Shelf marine and coastal facilities in the central Gulf Coast region (Burkett 2011). Many of California's power plants are at risk from sea level rise and the more extensive coastal storm flooding that results, especially in the low-lying San Francisco Bay area. Power plants and energy infrastructure in the coastal areas of U.S. regions face similar risks.

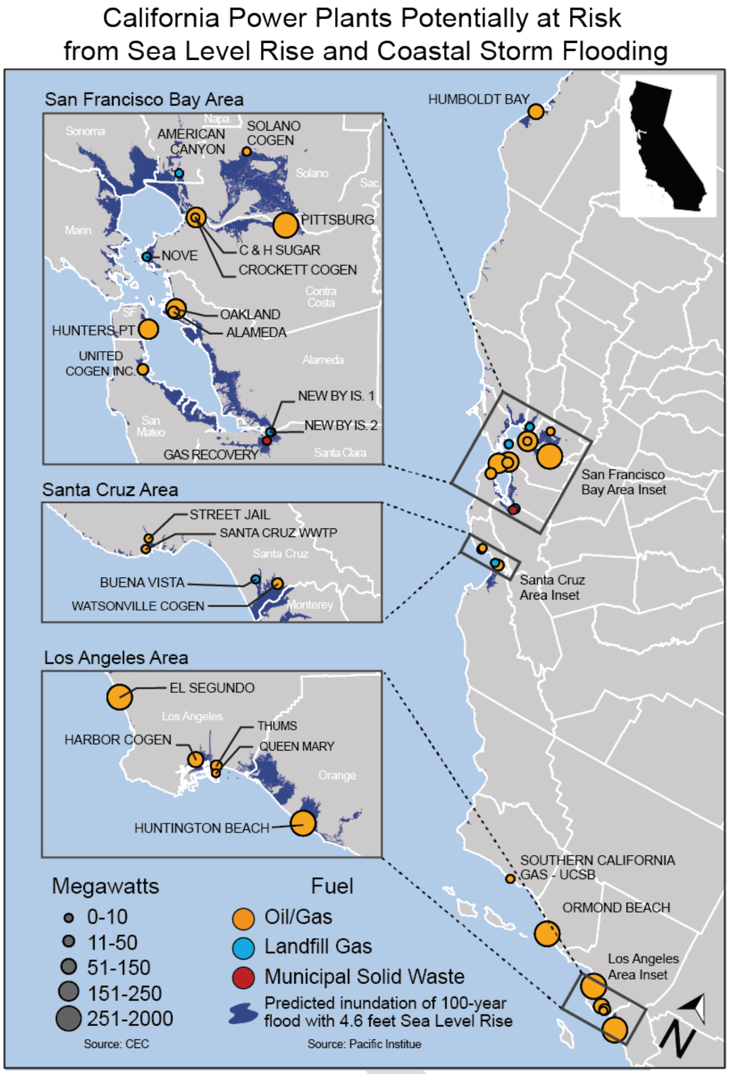

Figure 4.5: California Power Plants Potentially at Risk from Sea Level Rise and Coastal Storm Flooding

Caption: Rising sea levels will combine with storm surges and high tides to threaten power-generating facilities located in California coastal communities and around the San Francisco Bay (Source: Sathaye et al. 2011)

Possible Climate Resiliency and Adaptation Actions in Energy Sector

Table 2 summarizes actions that can be taken to increase the ease with which energy systems can adjust to climate change. Many of these adaptation investments entail "no regrets," providing short-term paybacks because they address current vulnerabilities as well as future risks.

Table 4.2. Possible Climate Resilience and Adaptation Actions in Energy Sector

Caption: Future energy production will be affected by a range of climate change impacts. Chart shows possible responses to anticipate and respond to these changes.

	Key Challenges Addressed			
Possible Actions	**Extreme Weather Events**	**Increase in Peak Energy Loads**	**Water Constraints on Energy Production**	**Sea Level Rise**
Supply: System and Operational Planning				
Diversifying Supply Chains	X	X	X	X
Strengthening and Coordinating Emergency Response Plans	X	X	X	
Providing remote/protected emergency-response coordination centers	X			
Developing flood-management plans or improving stormwater management	X			X
Developing drought-management plans for reduced cooling flows			X	
Developing hydropower management plans/policies addressing extremes			X	
Supply: Existing Equipment Modifications				
Hardening/building redundancy into facilities	X	X		
Elevating water-sensitive equipment or redesigning elevation of intake structures	X			X
Building coastal barriers, dikes, or levees	X			X
Improving reliability of grid systems through back-up power supply, intelligent controls, and distributed generation	X	X	X	
Insulating equipment for temperature extremes	X			

Implementing dry (air-cooled) or low-water hybrid (or recirculating) cooling systems for power plants			X	
Adding technologies/systems to pre-cool water discharges			X	
Using non-fresh water supplies: municipal effluent, brackish or seawater			X	
Relocating vulnerable facilities	X		X	X
Supply: New Equipment				
Adding peak generation, power storage capacity, and distributed generation	X	X	X	X
Adding back-up power supply for grid interruptions	X	X	X	
Increasing transmission capacity within and between regions	X	X	X	X
Use: Reduce Energy Demand				
Improving building energy, cooling-system and manufacturing efficiencies, and demand-response capabilities (for example, smart grid)	X	X		
Setting higher ambient temperatures in buildings	X	X		
Improving irrigation and water distribution/reuse efficiency		X	X	
Allowing flexible work schedules to transfer energy use to off-peak hours		X		

Future Energy Systems

As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways – depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.

Today's energy systems vary significantly by region, with differences in climate-related impacts also introducing considerable variation by locale. Table 3 shows projected impacts of climate change on, and potential risks to, energy systems as they currently exist in different regions. Most vulnerabilities and risks for energy supply and use are unique to local situations, but others are national in scope. For example, biofuels production in three regions (Midwest, Great Plains and Southwest) could be impacted by the projected decrease in precipitation during the critical growing season in the summer months (Ch. 10: Water, Energy, and Land Use; Ch. 7: Forestry).

One certainty about energy systems in the future is that they will be different than today's, but in ways not yet known. Many uncertainties – financial, economic, regulatory, technological, and so on – will affect private and public consumption and investment decisions on energy fuels, infrastructure, and systems. Energy systems will evolve over time, depending upon myriad choices made by countless decision-makers responding to changing conditions in markets, technologies, policies, consumer preferences, and climate. A key challenge to understanding the nature and intensity of climate impacts on future energy systems is the amount of uncertainty regarding future choices about energy technologies and their deployment. An evolving energy system is also an opportunity to develop an energy system that is less vulnerable to climate change.

Table 4.3: Energy Supply: Summary of National and Regional Impacts, Challenges and Opportunities

Caption: Increased temperatures, changing precipitation patterns, and sea level rise will affect many sectors and regions, including energy production, agriculture yields, and infrastructure damage.

	Consequences[1]: Challenges and Opportunities								
	Fuel Extraction, Production, and Refining		Fuel Distri-bution	Electricity Generation					Electricity Distribution
Region	Hydrocarbons[2]	Biofuels	Trans-port/ Pipelines	Hydro-power	Solar PV Wind	Thermal Power Generation[3]			
Physical Impacts – High Likelihood	Increased ambient temperature of air and water	Increased extremes in water availability	Coastal erosion and sea level rise	Increased extremes in water availability	Impacts projected but not well defined at this time.	Increased ambient temperature of air and water	Increased extremes in water availability	Coastal erosion and sea level rise	Hot summer periods
National Trend Summary[6] - Consequence	Decreased production and refining capacity	Decreased agricultural yields	Damage to facilities	Reduced electricity production		Reduced plant efficiency and cooling capacity	Interruptions to cooling systems	Damage to facilities	Reduced capacity/ damage to lines
Key Indicator (2071-2099 vs 1971-2000)	Mean Annual Temperature[4]	Summer Precipitation[4]	Sea Level Rise[5] (2100)	Days <0.1 inch[6] (2055)		Mean Annual Temperature[4]	Summer Precipitation[4]	Sea Level Rise[5] (2100)	# Days > 90F[6,7] (2055)
Northeast	+ 4.3 to 7.9 F	- 5 to + 6%	0.5 – 1.2 m	+1 day		+ 4.3 to 7.9 F	- 5 to + 6%	0.5 – 1.2 m	+ 13 days
Southeast	+ 4.3 to 7.9 F	- 22 to + 9%	0.5 – 1.2 m	+ 2 days		+ 4.3 to 7.9 F	- 22 to + 9%	0.5 – 1.2 m	+ 31 days
Midwest	+ 4.5 to 8.1 F	- 22 to + 6%	No coast	+ 0 days		+ 4.5 to 8.1 F	- 22 to + 6%	No coast	+ 19 days
Great Plains	+ 4.5 to 8 F	- 27 to + 5%	0.5 – 1.2 m	+ 3 days		+4.5 to 8 F	- 27 to + 5%	0.5 – 1.2 m	+ 20 days
Southwest	+ 4.5 to 8.3 F	-13 to +3%	0.5 – 1.2 m	+ 10 days		+ 4.5 to 8.3 F	-13 to +3%	0.5 – 1.2 m	+ 24 days
Northwest	+ 4.2 to 7.9 F	- 34 to – 11%	0.5 – 1.2 m	+ 6 days		+ 4.2 to 7.9 F	- 34 to – 11%	0.5 – 1.2 m	+ 4 days
Alaska	+ 4.4 to +8.1 F	+14 to +25%	0.5 – 1.2 m	No projection		+ 4.4 to 8.1 F	+14 to +25%	0.5 – 1.2 m	No projection.
Pacific Islands	+2.5 to + 4.5 F	Range from little change to increases	0.5 – 1.2 m	No projection		+2.5 to + 4.5 F	Range from little change to increases	0.5 – 1.2 m	No projection

Notes

1. Excludes extreme weather events.
2. Hydrocarbons includes coal, oil, and gas including shales.
3. Thermal power generation includes power plants fired from nuclear, coal, gas, oil, biomass fuels, solar thermal, and geothermal energy.
4. CMIP3 15 GCM Models: 2070–2099 Median Projection SRES B1 – A2 (versus 1971–2000)
5. 2100: Low Intermediate to High Intermediate Scenario from Sea Level Change Scenarios for the US National Climate Assessment (Parris et al. 2012). Range is similar to the 1 to 4 feet of sea level rise projected in Ch. 2: Our Changing Climate, Key Message 9.
6. 2055 NARCCAP
7. References: (Clarke et al. 2007; Wilbanks et al. 2012a)
8. Notes: Red cells denote negative impacts; green cells denote positive impacts.

Very different future energy supply portfolios are possible depending upon key economic assumptions including what a carbon management program, if any, looks like (Clarke et al. 2007; EIA 2008; EPRI 2011), and whether significant changes in consumption patterns occur for a variety of other reasons. Renewable energy sources, including solar, wind, and biofuels, are meeting a larger portion of U.S. demand, and there is the opportunity for this contribution to increase in the future (Ch. 6: Agriculture; Ch. 7: Forestry). This fundamental uncertainty about the evolving character of energy systems contributes another layer of complexity to understanding how climate changes will impact energy systems.

As they consider actions to enhance the resiliency of energy systems, decision makers confront issues with current energy systems as well as possible future configurations. The systems will evolve, and will be more resilient over time if actions tied to today's systems features do not make future systems less resilient as a result. For example, if moving toward biomass as an energy source involves more water-consumptive energy supplies that could be constrained by drier future climate conditions, then decisions about energy choices should be made in the context of understanding these trends.

Because U.S. energy decisions tend to be made in regulated markets rather than centrally planned, these decisions are unpredictable, even though they can be expected to evolve with the changing climate conditions. These trends in use patterns may continue into the future; this is an opportunity to increase resilience but also a major uncertainty for energy utilities and policy makers. Energy infrastructure tends to be long-lived, so resiliency can be enhanced by more deliberate applications of risk-management techniques and information about anticipated climate impacts and trends (NRC 2011).

For example, risk-management approaches informed by evolving climate conditions could be used to project the value of research and development on, or investments in, construction of dikes and barriers for coastal facilities or for dry-cooling technologies for power plants in regions where water is already in short supply. Solar and wind electricity generation facilities could be sited in areas that are initially more expensive (such as offshore areas) but less subject to large reductions in power plant output resulting from climatic changes. Target installed reserve margins for electric generating capacity and capacity of power lines can be established using certain temperature expectations, but adjusted as conditions unfold over time.

Traceable Accounts

Chapter 4. Energy Supply and Use

Key Message Process: The author team met bi-weekly by teleconference. Early in the development of key messages and a chapter outline, the authors reviewed all relevant technical input reports. Selected authors participated in a DOE sponsored workshop on Energy Supply and Use, December 29-30, 2011 in Washington, D.C. The workshop was organized specifically to inform a DOE technical input report and the 2013 NCA and to engage stakeholders in this process. The authors selected key messages based on the risk and likelihood of impacts, associated consequences, and available evidence. Relevance to decision support within the energy sector was also an important criteria.

The U.S. maintains extensive data on energy supply and use. The Energy Information Administration (EIA) of the U.S. Department of Energy is a primary organization in this activity, and data with quality control, quality assurance, and expert review are available through EIA Web pages.

Key message #1/5	**Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of extreme weather events are expected to increase.**
Description of evidence base	A series of NCA workshops reviewed potential influences of climate change thus far on the frequency and intensity of extreme events (Peterson et al. 2012). Numerous past extreme events demonstrate damage to energy facilities and infrastructure. Data assembled and reviewed by the Federal Government summarize typical costs associated with damage to energy facilities by major extreme events. State and regional reports as well as data provided by public utilities document specific examples. Damage to Gulf Coast energy facilities and infrastructure by Hurricanes Katrina and Rita provides excellent examples to support this key message (Entergy Corporation 2012; Hibbard 2006; Rosenzweig et al. 2009). Wildfire also damages transmission grids (Sathaye et al. 2011). The authors benefited from Agency sponsored technical input reports summarizing relevant data and information on energy supply and use as well as urban systems and infrastructure(Wilbanks et al. 2012b; Wilbanks et al. 2012a). A number of other technical input reports were relevant as well. These were reviewed carefully, particularly with regard to the identification of key messages.
New information and remaining uncertainties	A series of NCA workshops provided a summary of current evidence for influences of climate change on the frequency and intensity of extreme events. These summaries provide succinct evidence that certain extreme events that damage energy facilities and infrastructure can be expected to increase in number and intensity with climate change. Documentation of damage to energy facilities and infrastructure continues to accumulate, increasing confidence in this key message (EIA 2008; NOAA 2011). The regional and local character of extreme events varies substantially, and this variability is a source of significant uncertainty regarding the impacts of climate change and consequences in terms of damage to energy facilities by extreme events. Additionally, damage to energy infrastructure in a specific location can have far-reaching consequences for energy production and distribution, and synthesis of such indirect consequences for production and distribution does not yet support detailed

	projections.
Assessment of confidence based on evidence	**High**. There is high consensus with moderate evidence that extreme weather events associated with climate change will increase disruptions of infrastructure services in some locations.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 4: Energy Supply and Use

Key Message Process: See key message #1.

Key message #2/5	**Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net energy use is projected to increase as rising demands for cooling outpace declining heating energy demands.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the energy supply and use technical input (Wilbanks et al. 2012a). Global climate models simulate increases in summer temperatures, and the NCA climate outlooks (Kunkel et al., 2012) describe this aspect of climate change projections for use in preparing the 2013 report (Ch. 2: Our Changing Climate). Data used by (Kunkel et al. 2012a) and Census Bureau population data, synthesized by the EIA were the basis for calculating population-weighted heating and cooling degree-days over the historic period as well as projections assuming SRES B1 and A2 scenarios. (Kunkel et al. 2012a) projects an increase in the number of cooling days and decrease in heating days, with peak electricity demand in some regions shifting from winter to summer (Wei 2012) and shifting to electricity needs for cooling instead of fossil fuels for heating (Clarke et al. 2007; Wei 2012; Williams et al. 2012).
New information and remaining uncertainties	While there is little uncertainty that peak electricity demands will increase with warming by climate change, substantial regional variability is expected. Climate change projections do not provide sufficient spatial and temporal detail to fully analyze these consequences. Socioeconomic factors including population changes, economic conditions, energy prices as well as technological developments in electricity generation and industrial equipment will have a strong bearing on electricity demands, specific to each region of the country.
Assessment of confidence based on evidence	**High**. Assuming specific climate change scenarios, the consequences for heating and cooling buildings are reasonably predictable, especially for the residential sector. With a shift to higher summer demands for electricity, peak demands for electricity can be expected to increase.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 4: Energy Supply and Use

Key Message Process: See key message #1.

Key message #3/5	**Both episodic and long-lasting changes in water availability will constrain different forms of energy production.**
Description of evidence base	Technical input reports summarize data and studies showing that changes in water availability will affect energy production (Skaggs et al. 2012; Wilbanks et al. 2012a), and more specifically, that water shortages will constrain electricity production (Averyt et al. 2011). Ch. 10: Water, Energy, and Land Use describes the impacts of drought in Texas during 2011 as an example of the consequences of water shortages for energy production as well as other uses (Ch. 10: Water, Energy, and Land Use). Electric utility industry reports document potential consequences for operation of generating facilities (EPRI 2011). A number of power plants across the country have experienced interruptions due to water shortages. Climate outlooks prepared for the NCA (Kunkel et al. 2012a) describe decreases in precipitation under the SRES A2 scenario, with the largest decreases across the Northwest and Southwest in the spring and summer.
New information and remaining uncertainties	An increasing number of documented incidents of interruptions in energy production due to water shortages provide stronger evidence that decreased precipitation or drought will have consequences for energy production. There is little uncertainty that water shortages due to climate change would affect energy production. But uncertainty about changes in precipitation and moisture regimes simulated by global climate models is significantly higher than for simulated warming. Additionally, climate change simulations lack the spatial and temporal detail required to analyze the consequences for water availability at scales relevant to decisions about changes in energy facilities to reduce risk or adapt to water shortages associated with climate change.
Assessment of confidence based on evidence	**High**. The evidence is compelling that insufficient water availability with climate change will affect energy production; however, simulations of climate change lack the detail needed to provide more specific information for decision support.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 4: Energy Supply and Use

Key Message Process: See key message #1.

Key message #4/5	**In the longer term, sea level rise will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.**
Description of evidence base	The sea level change scenario report prepared for the NCA (Parris et al. 2012, in press) and Ch. 2: Our Changing Climate provide further information about sea level change. Data available through the EIA provide high-quality information about the locations and distribution of energy facilities. A substantial portion of the Nation's energy facilities and infrastructure are located along coasts or off-shore, and sea level rise will affect these facilities (Burkett 2011; Sathaye et al. 2011; Wilbanks et al. 2012b; Wilbanks et al. 2012a).
New information and remaining uncertainties	Projections of sea level change are relatively uncertain compared to other aspects of climate change. More importantly, there will be substantial variability in region and local sea level change, and facilities exposed to more frequent and intense extreme wind and precipitation events will be at higher risk. Data and analyses to understand regional and local sea level change are improving, but substantial uncertainty remains and decision support for adaptation is challenged by these limitations.
Assessment of confidence based on evidence	**High**. There is high confidence that increases in global mean sea level will affect coastal energy facilities; however, regional and local details are less certain.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 4: Energy Supply and Use

Key Message Process: See key message #1.

Key message #5/5	**As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways – depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.**
Description of evidence base	A number of studies describe U.S. energy system configurations in terms of supply and use assuming different scenarios of climate change, including SRES B1 and A2 (Clarke et al. 2007; EIA 2008; EPRI 2011). A technical input report to the NCA by DOE (Wilbanks et al. 2012b; Wilbanks et al. 2012a) provides details and updates earlier studies. The potential role of biofuels is described within Chapters 6 and 7 of this report (Ch. 6: Agriculture; Ch. 7: Forestry).
New information and remaining uncertainties	As the EIA and other organizations update data and information about U.S. energy systems as well as projections of the mix of primary energy under various assumptions about demographic, economic, and factors, understanding of options for future energy supply and use within the U.S. improves. With additional data and better models, alternative energy mixes can be explored with respect to climate change adaptation and mitigation. But numerous factors that are very difficult to predict affect the deployment of actual facilities and infrastructure.
Assessment of confidence based on evidence	**High**. There is high confidence that U.S. energy systems will evolve in ways that affect risk with respect to climate change and options for adaptation or mitigation.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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5. Transportation

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Key Messages:

1. **The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are reducing the reliability and capacity of the U.S. transportation system in many ways.**
2. **Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**
3. **Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.**
4. **Climate change impacts will increase costs to transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.**

The U.S. economy depends on the personal and freight mobility provided by the country's transportation system. Essential products and services like energy, food, manufacturing, and trade all depend in interrelated ways on the reliable functioning of these transportation components. Disruptions to transportation systems, therefore, can cause large economic and personal losses. The national transportation system is composed of four main components that are increasingly vulnerable to climate-change impacts:

- Fixed node infrastructure, such as ports, airports, and rail terminals
- Fixed route infrastructure, such as roads, bridges, locks, canals/channels, railways, and pipelines, mostly publicly owned and/or managed
- Vehicles, such as cars, buses, and trucks; railcars and locomotives; ships and barges; and aircraft – all mostly privately owned
- The people, institutions, laws, policies, and information systems that convert infrastructure and vehicles into working transportation networks

Transportation systems influence future climate characteristics and are also affected by changes in the climate. In 2010, the U.S. transportation sector accounted for 27% of U.S. greenhouse gas emissions (also called heat-trapping gas emissions) (Source: EPA 2011). Petroleum accounts for 93% of the nation's transportation energy use (EIA 2011), while cars and trucks account for 65% of transportation emissions (EPA 2011).

Transportation systems are already experiencing costly climate change related impacts. Many inland states – for example, Vermont, Tennessee, Iowa, and Missouri – have experienced severe precipitation events and flooding during the past three years, damaging roads, bridges, and rail systems. Over the coming decades, all modes and regions will be affected by increasing temperatures, more extreme weather events, and changes in precipitation. Concentrated transportation impacts are likely in Alaska and along seacoasts.

Transportation systems require expensive and long-lived (typically 50 to 100 years) infrastructure. The estimated value of U.S. transportation facilities in 2010 was $4.1 trillion (U.S. Bureau of Economic Analysis 2011). As climatic conditions shift, portions of this infrastructure will increasingly be subject to climatic stresses that will reduce the reliability and capacity of transportation systems (NRC 2008). Transportation systems are also vulnerable to interruptions in fuel and electricity supply, as well as communications disruptions – which are also subject to climatic stresses (NRC 2008). Power outages resulting from Hurricane Katrina shut down three major petroleum pipelines for two days, and the systems operated at reduced capacities for two weeks (Wilbanks et al. 2012) .

Climate change will affect transportation systems directly, through infrastructure damage, and indirectly, through changes in trade flows, agriculture, energy use, and settlement patterns. If, for instance, corn cultivation shifts northward in response to rising temperatures, U.S. agricultural products may flow to markets from different origins by different routes (Vedenov et al. 2011). If policy measures and technological changes reduce greenhouse gas emissions by affecting fuel types, there will likely be significant impacts on the transportation of energy supplies (pipelines, coal trains, and so on) and on the cost of transportation to freight and passenger users (CCSP 2008).

Disruptions to transportation system capacity and reliability can be partially offset by adaptations. Transportation systems *as networks* may use alternative routes around damaged elements or shift traffic to undamaged modes. Other adaptation actions include: new infrastructure designs for future climate conditions, asset management programs, at-risk asset protection, operational changes, and abandoning/relocating infrastructure assets that would be too expensive to protect.

Reliability and Capacity at Risk

The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are reducing the reliability and capacity of the U.S. transportation system in many ways.

Global climate change has both gradual and extreme event implications. A gradually warmer climate and increased drought in the Southeast and the Southwest will affect slope stability and cause pavement buckling that will damage infrastructure like roads and rail lines. Streamflows based on increasingly more frequent and intense rainfall instead of slower snowmelt could increase the likelihood of bridge damage from faster-flowing streams. However, less snow in some areas will reduce snow removal costs and extend construction seasons. Shifts in agricultural production patterns will necessitate changes in transportation routes and modes.

Climate models project that extreme heat and heat waves will become more intense, longer lasting, and more frequent. By 2080-2100, average temperatures are expected to increase by 3°F to 6°F for the continental U.S., assuming emissions reductions from current trends (B1 scenario), while continued increases in emissions (A2 scenario) would lead to an increase in average temperatures ranging from 5°F in Florida to 9°F in the upper Midwest (Kunkel et al. 2012a).

The impact on transportation systems not designed for such high temperatures would be severe. Expansion joints on bridges and highways are stressed and asphalt pavements deteriorate more rapidly at higher temperatures (Meyer et al. 2010). Rail track stresses and track buckling will increase (Hodges 2011; Rossetti 2002). Lift-off limits at hot-weather and high-altitude airports will reduce aircraft operations (Kulesa 2003).

Construction crews may have to operate on altered time schedules to avoid the heat of the day, with greater safety risks for workers (NIOSH 1986). The construction season may lengthen in many localities. Similarly, higher temperatures (and precipitation changes) are likely to affect transit ridership, bicycling, and walking in various ways.

Climate change is most severe at high northern latitudes. Alaska has experienced a 3°F rise in average temperatures since 1949 (Stewart et al. 2012), double the rest of the country. Winter temperatures have risen by 5°F. On the North Slope, sea ice formerly provided protection to the shoreline against strong fall/winter winds and storms. Retreating ice reduces this protection, eroding the shoreline and endangering villages. Thawing permafrost is causing pavement, runway, rail, and pipeline displacements, creating problems for operation and maintenance, and requiring reconstruction of key facilities. Arctic warming is also projected to allow the seasonal opening of the Northwest Passage to freight shipment (Arctic Council 2009).

Box 1: Thawing Alaska

Permafrost – soil saturated with frozen water – is a key feature of the Alaskan landscape. *Frozen* permafrost is a suitable base for transportation infrastructure such as roads and airfields. In rapidly warming Alaska, however, as permafrost thaws into mud, road shoulders slump, highway cuts slide, and runways sink. Alaska currently spends an extra $10 million per year repairing permafrost damage (Adaptation Advisory Committee 2010).

A recent study, which examined potential climate damage to Alaskan public infrastructure using results from three different climate models (Larsen 2007), considered 253 airports, 853 bridges, 131 harbors, 819 miles of railroad, 4,576 miles of paved, and 5,000 miles of unpaved road that could be affected by climate change. The present value of additional public infrastructure costs due to climate change impacts was estimated at $5.6 to $7.6 billion through 2080, or 10% to 12% of total public infrastructure costs in Alaska, which might be reduced by 40% with strong adaptation actions (Larsen 2007; Larsen et al. 2008).

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Impact of Sea Level Rise and Storm Surge on Mobile, Alabama

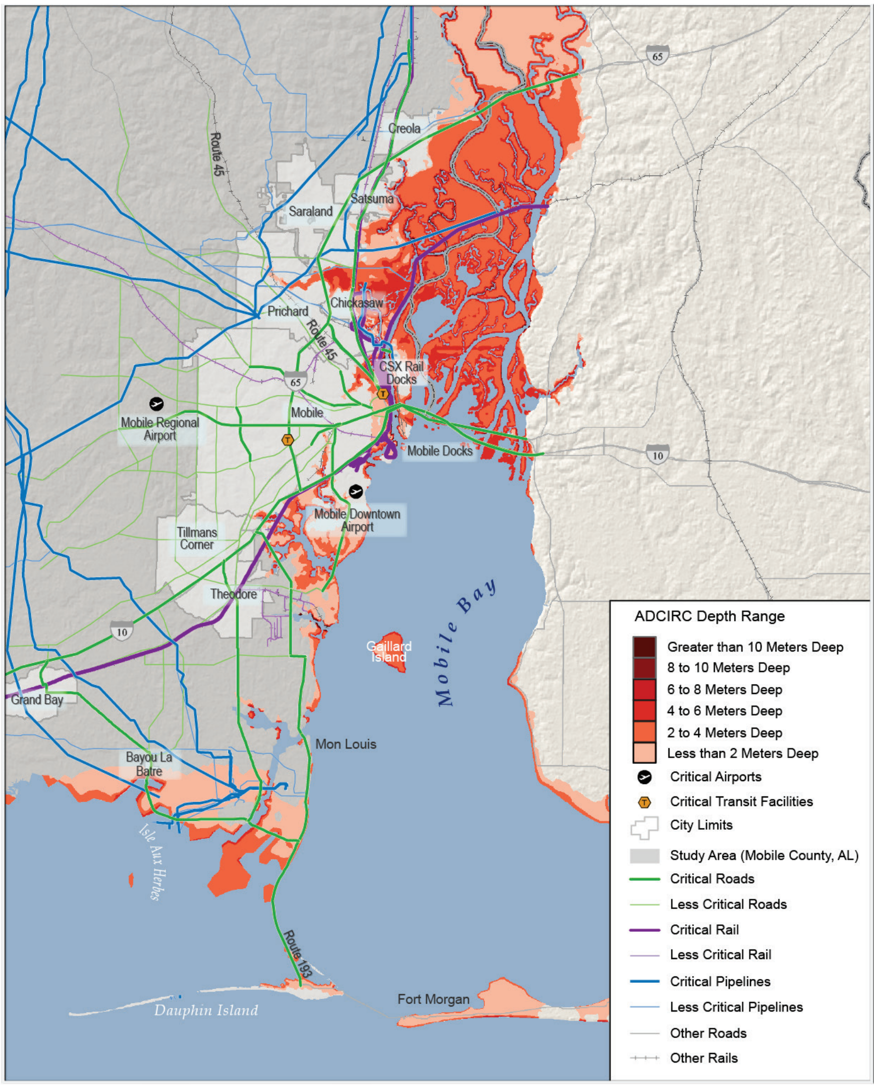

Figure 5.1: Impact of Sea Level Rise and Storm Surge on Mobile, Alabama

Caption: Many coastal areas in the U.S., including the Gulf Coast, are especially vulnerable to sea level rise impacts on transportation systems. This map shows that many parts of Mobile, Alabama, including critical roads, rail lines, and pipelines, would be exposed to storm surge under a scenario of a 30-inch sea level rise combined with a storm similar to Hurricane Katrina. A 30-inch sea level scenario is within the range projected for global sea level rise (Ch. 2: Our Changing Climate, Key Message 9). (Source: DOT 2012).

Coastal Impacts

Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.

The transportation impacts of rising sea levels, which are expected to continue rising by an additional 1 to 4 feet in this century (See also Ch. 2: Our Changing Climate, Key Message 9) (NCA/SLCS Team 2011), will vary widely by location and geography. When sea level rise is coupled with intense storms, the resulting storm surges will be greater, extend farther inland, and cause more extensive damage. Ports and harbors will need to be reconfigured to accommodate higher seas. Many of the nation's largest ports are along the Gulf Coast, which is especially vulnerable due to a combination of sea level rise, storm surges, erosion, and land subsidence. In 2011, the U.S. had net imports of 45% of oil consumed and 56% of the imports passed through Gulf Coast ports (EIA 2012).

More frequent disruptions and damage to roads, tracks, runways, and navigation channels are projected in coastal areas beyond the Gulf Coast. Thirteen of the nation's largest airports have at least one runway with an elevation within 12 feet of current sea levels (Airnav LLC 2012). Most ocean-going ports are in low-lying coastal areas, including two of the most important for imports and exports: Los Angeles/Long Beach and Galveston/Houston. Many federally maintained navigation channels have deteriorated in recent years to dimensions less than those authorized, which has resulted in reduced levels of service that affect navigation safety and reliability (U.S. Army Research and Development Center 2009). Extreme floods and storms associated with climate change will lead to increased movement of sediment and build up of sandy formations in channels. Channels that are not well maintained and have less sedimentation storage volume will thus be more vulnerable to significant, abrupt losses in navigation service levels. Additional channel storage capacity that may be created by sea level rise will also increase water depths and increase sedimentation in channels. See Ch. 25: Coastal Zone Development and Ecosystems for additional discussion of coastal transportation impacts.

Airport Runways Near Sea Level

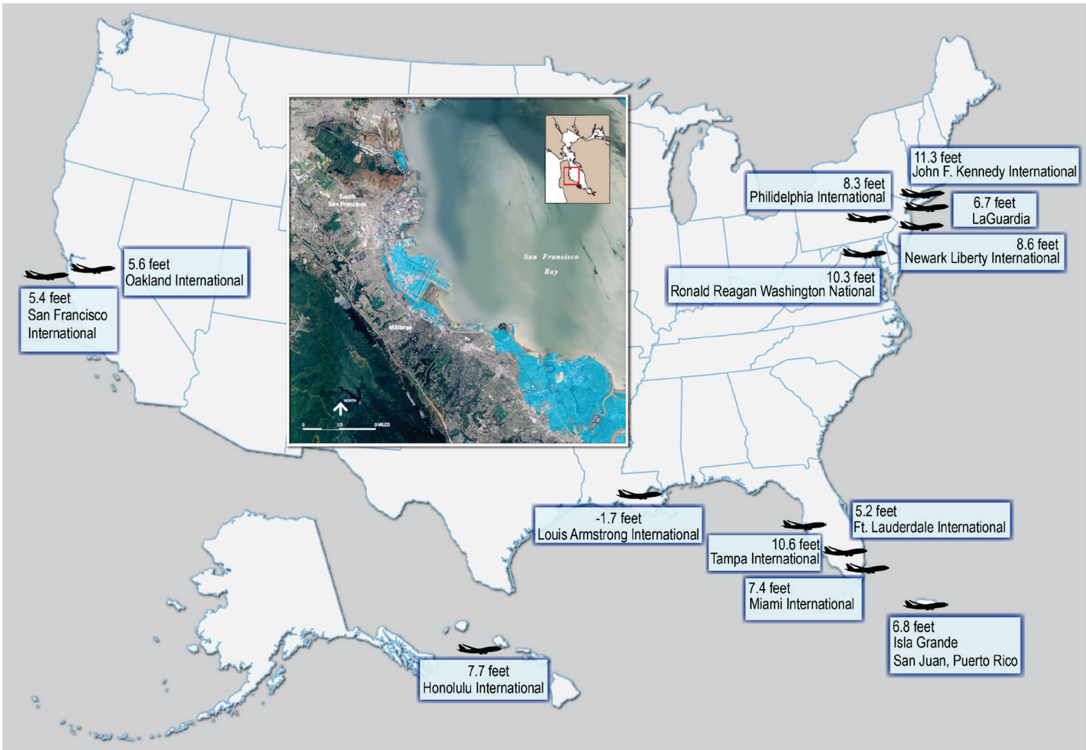

Figure 5.2: Airport Runways Near Sea Level

Caption: Thirteen of the largest airports in the U.S. have at least one runway with an elevation within 12 feet of current sea level (Reference: www.airnav.com/airports). Sea level rise will pose a threat to low-lying infrastructure such as these. The inset is U.S. Geological Survey data of San Francisco Bay showing areas (in blue) which are susceptible to 16 inches of sea level rise by 2050 (San Francisco Bay Conservation and Development Commission), which is within the range projected for global sea level rise in Ch. 2: Our Changing Climate.

Weather Disruptions

Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.

Changes in precipitation patterns, particularly more intense storms and drought, will affect transportation systems across the country. Severe storm delays disrupt almost all types of transportation. Storm drainage systems for highways, tunnels, airports, and city streets could prove inadequate, resulting in localized flooding. Bridge piers are subject to scour as runoff increases stream and river flows, potentially weakening bridge foundations. Severe storms will disrupt highway traffic leading to more accidents and delays. More airline traffic will be delayed or canceled.

Inland waterways may well experience greater floods, with high flow velocities that are unsafe for navigation and shut channels down intermittently. Numerous studies indicate that there is increasing severity and frequency of flooding throughout much of the Mississippi and Missouri River Basins (Black 2008; Criss and Schock 2001). In the Upper Mississippi/Missouri Rivers, there have been two 300- to 500-year floods over the past 20 years (Holmes et al. 2008). Drought increases the probability of wildfires, which affect visibility severely enough to close roads and airports. Drought can lower vessel drafts on navigable rivers and associated lock and dam pools. Less ice formation on navigable waterways has the potential to increase seasonal windows for passage of navigation.

Hurricanes in the Atlantic are expected to increase in intensity and frequency (see Ch. 2: Our Changing Climate, Key Message 8). As hurricanes approach landfall, they create storm surge, which may carry water far inland. The resulting flooding, wind damage, and bridge destruction disrupts virtually all transportation systems in the affected area.

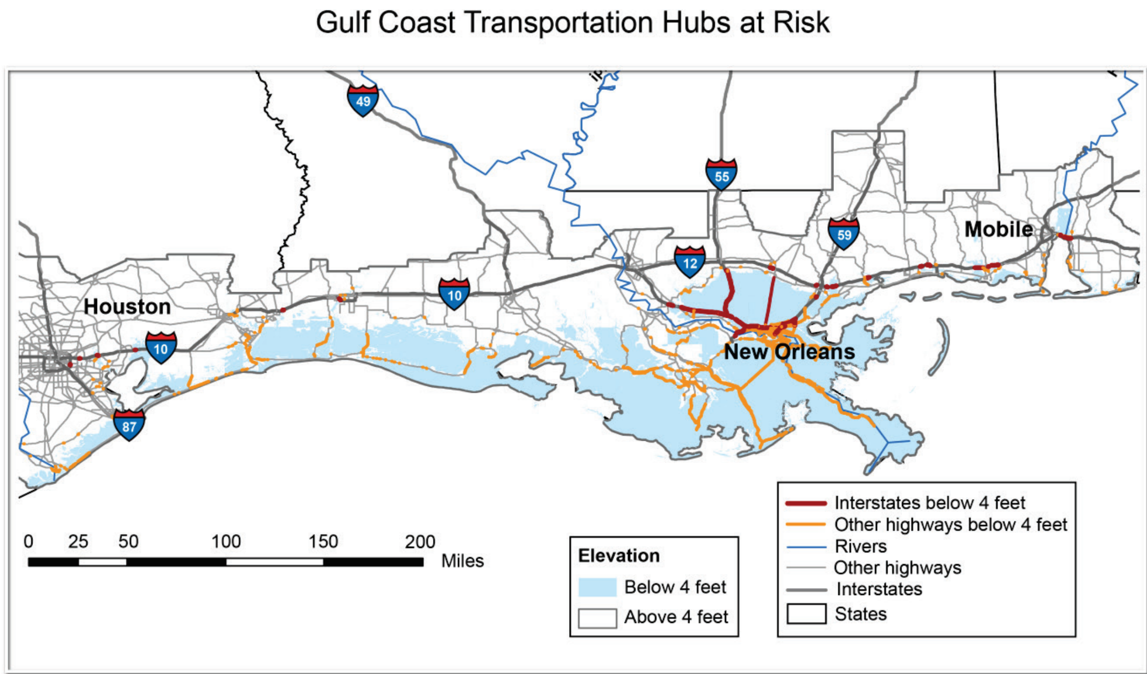

Figure 5.3: Gulf Coast Transportation Hubs at Risk

Caption: Within this century, 2,400 miles of major roadway are projected to be inundated by sea level rise in the Gulf Coast region. The map shows roadways at risk in the event of a sea level rise of about 4 feet, which is within the range of projections for this region in this century (see also Ch. 2: Our Changing Climate, Key Message 9). In total, 24% of interstate highway miles and 28% of secondary road miles in the Gulf Coast region are at elevations below 4 feet. Source: 2009 NCA/CCSP SAP 4.7

Box 2: Hurricane Sandy

On October 29, 2012, Hurricane Sandy dealt the transportation systems of New Jersey and New York and environs a massive blow, much in line with vulnerability assessments conducted over the past four years (Jacob et al. 2008; New York State 2011; New York State Sea Level Rise Task Force 2010; Zimmerman and Faris 2010). All tunnels and most bridges leading into New York City were closed during the storm. A nearly fourteen-foot storm surge (The New York Times 2012) flooded the Queens Midtown, Holland, and Carey (Brooklyn Battery) tunnels, which remained closed for at least one week (two weeks for the Carey Tunnel) while floodwaters were being pumped out and power restored. The three major airports, Kennedy, Newark, and LaGuardia, flooded, with LaGuardia absorbing the worst impact and closing for three days (The Port Authority of New York & New Jersey 2012a). Almost 7.5 million passengers per day ride the New York City subways and buses (Metropolitan Transportation Authority 2012a). Much of the New York City subway system below 34th Street was flooded, including all seven tunnels under the East River to Brooklyn and Queens. In addition to removing the floodwaters, all electrical signaling and power systems (the third rails) had to be cleaned, inspected, and repaired. Service on most Lower Manhattan subways was suspended for at least one week (Vantuono

2012), as was the PATH system to New Jersey (The Port Authority of New York & New Jersey 2012b). Commuter rail service with over 500,000 passengers per day (Metropolitan Transportation Authority 2012a) to New Jersey, Long Island, and northern suburbs was similarly affected for days or weeks with flooded tunnels, downed trees and large debris on tracks, and loss of electrical power (Metropolitan Transportation Authority 2012b). All of this disruption was in addition to the miles of local roads, streets, underpasses, parking garages, and bridges flooded and/or badly damaged in the region, and countless parked vehicles that sustained water damage. Flooded roadways prevented the New York Fire Department from responding to a fire that destroyed over 100 homes in the Breezy Point neighborhood of Brooklyn (Hampson 2012).

Hurricane Sandy's storm surge produced nearly four feet of floodwaters throughout the Port of New York and New Jersey, damaging electrical systems, highways and rail track, and port cargo, displacing hundreds of shipping containers, and causing ships to run aground (The Port Authority of New York & New Jersey 2012c). Floating debris, wrecks, and obstructions in the channel had to be cleared before the Port was able to reopen to incoming vessels within a week (U.S. Army Corps of Egineers 2012, personal communication). Pleasure boats were damaged at marinas throughout the region. On a positive note, the vulnerability analyses prepared by the metropolitan New York authorities and referenced above provided a framework for efforts to control the damage and restore service more rapidly. Noteworthy are the efforts of the Metropolitan Transit Authority to protect vital electrical systems and restore subway service to much of New York within four days.

The impacts of this extraordinary storm on one of the nation's most important transportation nodes were felt across the country. Airline schedules throughout the U.S. and internationally were snarled; Amtrak rail service along the East Coast and as far away as Buffalo and Montreal was curtailed; and freight shipments in and out of the hurricane impact zone were delayed. The resultant direct costs to the community and indirect costs to the economy will undoubtedly rise into the tens of billions of dollars. While the storm cannot be tied directly to climate change, given that tropical storms have hit the northeast before as late as December (Burt 2012), it is nevertheless indicative of what powerful tropical storms and higher sea levels could bring on a more frequent basis in the future.

Hurricane Sandy Causes Flooding in New York City Subway Stations

Figure 5.4: Hurricane Sandy Causes Flooding in New York City Subway Stations

Caption: The nation's busiest subway system sustained the worst damage in its 108 years of operation on October 29, 2012, as a result of Hurricane Sandy. Millions of people were left without service for at least one week after the storm, as the Metropolitan Transportation Authority rapidly worked to repair extensive flood damage (Vantuono 2012).

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Risks and Consequences

Risk is a function of both likelihood of impact and the consequences of that impact. Table 1 is an illustrative application of a risk matrix adapted from the Port Authority of New York and New Jersey. As shown, different types of climate-related incidents/events can have associated with them a likelihood of occurrence and a magnitude of the consequences if the incident does occur.

In assessing consequences, the intensity of system use, as well as the existence or lack of alternative routes, must be taken into account. Disabling a transportation facility can have ripple effects across a network, with trunk lines and hubs having the most widespread impacts (McLaughlin et al. 2011).

Table 5.1: Illustrative Risks of Climate-related Impacts

		Likelihood of Occurrence			
		Low	**Medium**	**High**	**Virtually Certain**
Magnitude of Consequences	**High**	Subway and tunnel flooding	Increased widespread flooding of transportation facilities	Major localized flooding disrupts transportation systems	Inundation of coastal assets due to storm surge
	Medium	Increased rock/mud slides blocking road and rail facilities	Train derailment due to rail buckling	Increased disruption of barge traffic due to flooding	Short-term road flooding and blocked culverts due to extreme events
	Low	Lower visibility from wildfires due to drought conditions	Northward shift of agricultural production places more demand and stress on roads and systems not prepared for higher volumes	Pavement heaving and reduced pavement life due to high temperatures	Inundation of local roads due to sea level rise
	Positive (beneficial)	Reduced flight cancellations due to fewer blizzards	Reduced maintenance costs for highways and airports due to warmer winters	Reduced Great Lakes Freezing, leading to longer shipping season	Longer seasonal opening of Northwest Passage

Note: Table 1 relates to overall national expectations. This kind of matrix is likely to be most valuable and accurate if used at the state/regional/local levels.

(Source: Adapted from McLaughlin et al. 2011).

Assessing the consequences of climate change should encompass the broad array of factors that influence the nation's transportation system, and should consider changes in population, society, technology, prices, regulation, and the economy that eventually affect transportation system performance (Jaroszweski et al. 2010). For example, the trend in recent years in the U.S. economy of adopting just-in-time logistics increases the vulnerability of businesses to day-to-day disruptions caused by weather and flooding.

Costs and Adaptation Options

Climate change impacts will increase costs to transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.

Adaptation strategies can be employed to reduce the impact of climate change related events and the resulting consequences. Consideration of adaptation strategies in the transportation sector is especially important in the following five areas:

- **Transportation and land-use planning:** deciding what infrastructure to build and where to build it, as well as planning for vulnerable areas of the community and impacts on specific population groups.
- **Vulnerability and risk assessment**: identifying existing vulnerable facilities and systems, together with the expected consequences.
- **New infrastructure design**: adapting new infrastructure designs that anticipate changing environmental and operational conditions.
- **Asset management**: adapting existing infrastructure and operations that respond to current and anticipated conditions, including changed maintenance practices and retrofits.
- **Emergency response:** anticipating expected disruptions from extreme weather events, and developing emergency response capability.

Role of Adaptive Strategies in Reducing Impacts and Consequences

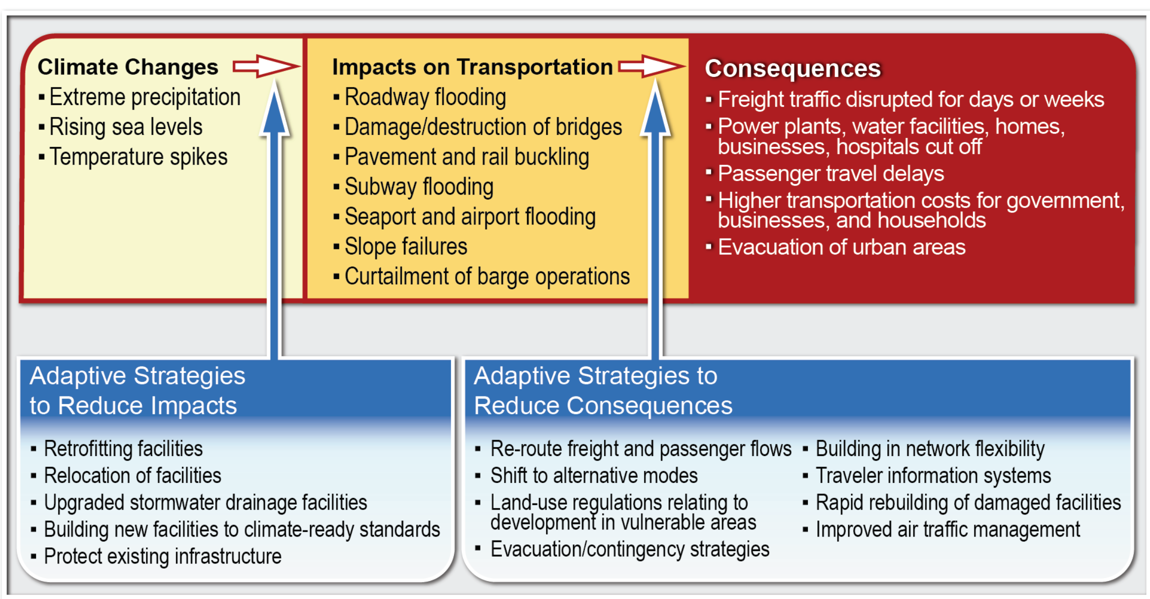

Figure 5.5: Role of Adaptive Strategies in Reducing Impacts and Consequences

Caption: Many projected climate change impacts and resulting consequences on transportation systems can be reduced through a combination of infrastructure modifications, improved information systems, and policy changes.

Adaptation takes place at multiple levels, from individual households and private businesses to federal, state, and local governments. The impacts associated with climate change are not new, since flooding, storm surge, and extreme heat have long been challenges. What is new is the changing frequency, intensity, and location/geography of impacts and hazards.

Responding effectively to present and future environmental challenges enhances the resilience of communities. Examples include improvements in storm water management, coastal zone management, and coastal evacuation plans.

At the national level, the transportation network has some capability to adjust to climate-related disruptions due to the presence of network redundancy – multiple routes are often possible for long-distance travel, and more than one mode of transportation may be used for travel. However, in some cases, only one major route connects major destinations, such as Interstate 5 between Seattle and San Francisco; movements along such links are particularly vulnerable to disruption.

Box 3: Winter Storm-Related Closures of I-5 and I-90 in Washington State, 2007–08

In December, 2007 heavy rainfall west of I-5, combined with melting snow from the mountains, created extremely high floodwaters in western Washington State. Six-hour rainfall amounts were near a 100-year event for areas in Southwest Washington. High winds, heavy rains, mudslides, and falling trees made travel unsafe on highways. Downed power lines blocked roads, and, in many urban areas, rainwater overwhelmed drainage systems and flooded roadways.

The combined economic impact in the I-5 and I-90 corridors was estimated at almost $75 million, of which some $47 million was associated with the I-5 disruption and $28 million with the I-90 corridor. Estimated highway damage from the winter storm was $18 million for state routes and another $39 million for city and county roads (WSDOT 2008).

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Disruptions to the nation's inland water system from floods or droughts can, and has, totally disrupted barge traffic. Severe droughts throughout the upper Midwest in 2012 reduced flows in the Missouri and Mississippi Rivers to near record levels, impacting barge traffic. Further flow decreases occasioned by reductions in discharges from the upper Missouri River dams are projected to close the rivers to barge traffic above St Louis by year-end 2012 (The Associated Press 2012). While alternative modes, such as rail and truck, may alleviate some of these disruptions, it is impractical to shift major product shipments such as Midwest grain to other modes of transportation – at least in the near term (Rypinski 2011). While extreme weather events will continue to cause flight cancellations and delays, many weather delays from non-extreme events are compounded by inadequacies in the current national air traffic management system (Oster and Strong 2008). Improvements in the air traffic system, such as those anticipated in the FAA's NextGEN (www.faa.gov/nextgen/), should reduce weather-related delays.

At the state and local level, there is less resilience to be gained by alternative routing, and impacts may be more intense. For example, significant local and regional disruption and economic costs could result from the flooding of assets as diverse as New York's subways, Iowa's roads, San Francisco's airports, and Vermont's bridges.

Climate change is one of many factors, and an increasingly important one, that must be addressed by state, regional, and local agencies as they plan for new and rehabilitated facilities. By incorporating climate change routinely into the planning process, governments can reduce the vulnerability to climate change impacts and take actions that enhance the resilience of the transportation system to adverse weather conditions. Indeed, governments at various levels are taking action as described below.

Land-use planning can reduce risk by avoiding new development in flood-prone areas; conserving open space to enhance drainage; and relocating or abandoning structures or roads that have experienced repeated flooding. The National Flood Insurance Program encourages buyouts of repetitive loss structures and preservation of open space by reducing flood insurance rates for communities that adopt these practices.

An important step in devising an adaptation plan is to assess vulnerabilities. The Federal Highway Administration funded pilot projects in five coastal states to test a conceptual framework for evaluating risk (DOT 2005). The framework identifies transportation assets, evaluates the likelihood of impact on specific assets, and assesses the seriousness of such impacts.

Several state and local governments have conducted additional vulnerability assessments that identify potential impacts to transportation systems, especially in coastal areas. Detailed work has been undertaken by New York City (Jacob et al. 2008; New York State Sea Level Rise Task Force 2010; Rosenzweig et al. 2011b; Zimmerman and Faris 2010), California (California Natural Resources Agency 2009), Massachusetts (Massachusetts Energy and Environmental Affairs 2011), Washington (Washington State University 2012), Florida, and Boston (City of Boston 2011).

Box 4: Planning for Climate Change

The Metropolitan Planning Organization in Charlotte County-Punta Gorda, Florida conducted long-range scenario planning that integrated climate change (CCMPO 2010). A "smart growth" scenario that concentrated growth in urban centers was compared with a "resilient growth" scenario that steered development away from areas vulnerable to sea level rise. Planners evaluated the scenarios based on projected transportation performance outcomes and selected a preferred scenario reflecting aspects of each alternative. Charlotte County exemplifies how local governments can incorporate aspects of climate change into transportation planning.

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Non-coastal states and regions have also begun to produce vulnerability assessments. Midwestern states including Wisconsin (WICCI 2011), Iowa (Iowa Climate Change Impacts Committee 2011), and Michigan (Michigan Department of Transportation 2012) have addressed increasing risk of flooded roadways and other impacts.

Transit systems are already implementing measures that reduce vulnerability to climate impacts, including rail buckling. Portland's transit agency has been installing expansion joints at vulnerable locations, improving reliability of rail service (Hodges 2011). In New York, ventilation grates are being elevated to reduce the risk of flooding (Jacob et al. 2008).

Transportation agencies are incorporating climate change into ongoing design activities. For example, the Alaska Department of Transportation spends more than $10 million annually on shoreline protection, relocations, and permafrost protection for roadways (see "Thawing Alaska" above) (Adaptation Advisory Committee 2010). In May 2011, the California Department of Transportation (Caltrans) issued guidance to their staff on whether and how to incorporate sea level rise into new project designs (Caltrans 2011).

States have begun to integrate climate impacts into Transportation Asset Management, a systematic process for monitoring the conditions of roads and transit facilities (Meyer et al. 2010; Radow and Neudorff 2011). Maryland is working to prioritize assets taking sea level rise and increased storm intensity into account, and is developing a tool to track assets and assess vulnerability (Slater 2011). Florida DOT continually monitors conditions on roads and bridges, and is developing a statewide inventory and action plan for high-risk bridges (Jacobs 2009). Among inland states, Michigan DOT has identified a wide range of operational and asset management changes to adjust to climate change (Michigan Department of Transportation 2012).

The risk of flooding for transportation infrastructure can be reduced by effective stormwater and stream/river management. Following Tropical Storm Irene, Vermont state agencies are working on stream and river management to reduce conditions that exacerbate flooding impacts on transportation (Tetreault 2011, Interview).

Box 5: Tropical Storm Irene Devastates Vermont Transportation in August 2011

In August of 2011, Vermont was inundated with rain and massive flooding from Tropical Storm Irene, closing down 146 segments of the state road system along with more than 200 bridges, at an estimated cost of up to $175 to $200 million for rebuilding state highways and bridges. An additional 2,000 or more municipal roads and nearly 1,000 culverts were damaged, and more than 200 miles of state-owned rail required repair (VANR 2012).

The volume of water was unprecedented, as was the power of the water in the rivers running through the state. Culverts and bridges were affected and slope stability was threatened as a result of the immense amount and power of water and subsequent flooding.

When asked about the lessons learned, VTrans indicated the importance of good maintenance of riverbeds as well as roads. VTrans is working with the Vermont Agency of Natural Resources, looking upstream and downstream at the structure of the rivers, recognizing that risk reduction may involve managing rivers as much as changing bridges or roadways.

Rich Tetreault of VTrans emphasized that "Certainly we will be looking to right-size the bridges and culverts that need to be replaced … Knowing that we do not have the funds to begin wholesale rebuilding of the entire highway network to withstand future flooding, we will also enhance our ability to respond" when future flooding occurs (Tetreault 2011, Interview).

Tropical Storm Impact on Vermont Road

Figure 5.6: Tropical Storm Impact on Vermont Road

Caption: Vermont Route 131, outside Cavendish, a week after Tropical Storm Irene unleashed severe precipitation and flooding that damaged many Vermont roads, bridges, and rail lines. Photo courtesy of Vermont Agency of Transportation.

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Effective asset management requires significant data and monitoring of transportation assets. Improved weather and road-condition information systems enable transportation system managers to anticipate and detect problems better and faster – enabling them to close systems if needed, alert motorists, and dispatch maintenance and snow-removal crews. As Michigan DOT has noted, the increasing changes in snowstorms means that existing models used for snow and ice removal procedures are no longer reliable, requiring better monitoring and new models, as well as better roadway condition detection systems (Michigan Department of Transportation 2012).

Similarly, regular maintenance and cleaning of urban levee and culvert systems reduces the risk of roads and rails being inundated by flooding.

Extreme weather, such as hurricanes or intense storms, stresses transportation at precisely the time when smooth operation is critical. Effective evacuation planning, including early warning systems, coordination across jurisdictional boundaries, and creating multiple evacuation routes builds preparedness. Identifying areas with high concentrations of vulnerable and special-needs populations (including elderly, disabled, and transit-dependent groups) enhances readiness, as does identifying assets such as school buses that can be deployed for households that do not own vehicles.

Traceable Accounts

Chapter 5: Transportation

Key Message Process: In developing key messages, the chapter author team engaged, via teleconference, in multiple technical discussions from January through May 2012 as they reviewed numerous peer reviewed publications. The author teams review included a foundational Technical Input Report for the National Climate Assessment, "Climate Impacts and U.S. Transportation (DOT 2012)", and approximately 20 additional technical inputs to the NCA. Other published literature and professional judgment were also considered as the chapter key messages were developed. The chapter author team met in St. Louis, MO in April 2012 for expert deliberation and finalization of key messages.

Key message #1/4	**The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are reducing the reliability and capacity of the U.S. transportation system in many ways.**
Description of evidence base	Climate impacts in the form of sea level rise, changing frequency of extreme weather events, heat waves, precipitation changes, Arctic warming, and other climatic conditions are documented in Ch. 2: Our Changing Climate of this report. Climate can be described as the frequency distribution of weather over time. The authors believe that climate change will affect the reliability and capacity of U.S. transportations systems because existing weather conditions, flooding and storm surge demonstrably affect U.S. transportation systems, and that, consequently, changes in the frequency of these conditions will inevitably affect transportation systems. This view is supported by multiple studies of the impacts of weather and climate change on particular transportation systems or particular regions. An aggregate summary of impacts of climate change on U.S. transportation can be found in (NRC 2008). A paper commissioned for this effort considers specific impacts of various forms of climate change on infrastructure: (Meyer 2008). The effects of climate on transit systems are summarized in (Hodges 2011). The impact of heat and other climate effects on rail systems are described by (Rossetti and Johnsen 2011). Future impacts of sea level rise and other climatic effects on transportation systems in the Gulf Coast were examined by (CCSP 2008) The impacts of climate change on New York State, including transportation system were undertaken by (Rosenzweig et al. 2011b). Weather impacts on road systems are discussed in (DOT 2012) and numerous other sources. Weather impacts on aviation operations are discussed in (Kulesa 2003) and numerous other sources. In addition, the key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation (DOT 2012)". Technical Input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Additional peer-reviewed publications discuss that Arctic warming is affecting existing Alaskan transportation infrastructure today, and is projected to allow the seasonal opening of the Northwest Passage to freight shipment (Arctic Council 2009) .

New information and remaining uncertainties	Recent changes in global sea level rise estimates documented in Ch.2: Our Changing Climate, Key Message 9 of this report have not been incorporated into existing regional studies of coastal areas. In addition, recent research by USGS on the interaction between seal level rise, wave action, and local geology have been incorporated in only a few studies (Gutierrez 2011). Specific estimate of climate change impacts on transportation are acutely sensitive to regional projections of climate change, and, in particular, to the scale, timing, and type of predicted precipitation. New (CMIP5-based) regional climate projections will therefore affect most existing specific estimates of climate change impacts on transportation. Transportation planning in the face of uncertainties about regional-scale climate impacts present particular challenges. Impacts of climate on transportation system operations, including safety and congestion, both on road systems and in aviation, have been little studied to date. The future evolution of society and the transportation systems that serve society is itself uncertain, making the evaluation of impacts on an uncertain future system itself uncertain. Adaptation can significantly ameliorate impacts on the transportation sector, however, evaluation of adaptation costs and strategies for the transportation sector is at a relatively early stage.
Assessment of confidence based on evidence	Given the evidence described above, the authors are highly confident that climate change will affect transportation systems. Confidence is high, given current climate projections, particularly sea level rise and extreme weather events, that transportation systems will be affected by climate change.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 5: Transportation

Key Message Process: See key message #1.

Key message #2/4	**Sea level rise coupled with storm surge will continue to increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.**
Description of evidence base	Estimates of sea level rise are documented in Ch. 2: Our Changing Climate, Key Message 9 of this report. The prospective impact of sea level rise and storm surge on transportation systems is illustrated by the impact of recent hurricanes on U.S. coastlines. In addition, research on impacts of sea level rise and storm surge on transportation assets in particular regions of the United States demonstrate the potential for major coastal impacts (CCSP 2008; Rosenzweig et al. 2011b) (Suarez et al. 2005), and numerous other reports. Note that most existing literature on storm surge and sea level rise impacts on transportation systems is based on a global sea level rise of less than one meter (about 3 feet). In addition, the key message and supporting text summarize extensive evidence documented in “Climate Impacts and U.S. Transportation (DOT 2012). Technical Input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.
New information and remaining uncertainties	As noted above, new estimates of sea level rise have overtaken most of the existing literature on transportation and sea level rise in the United States. In addition, it is not clear that the existing literature reflects recent USGS work on interactions between sea level rise, wave action, and local geology (Gutierrez 2011). New global sea level rise estimates will require development of new regional sea level rise estimates, as well as revision of erosion modeling, since transportation and other infrastructure impacts must necessarily be studied in a local context. Generally speaking, modeling of sea level rise impacts using existing USGS NED data has well-understood limitations. Since NED data is freely and easily available, it is often used for preliminary modeling. More accurate and more recent elevation data may be captured via LIDAR campaigns, and this data collection effort will be necessary for accurate understanding of regional and local sea level rise and storm surge impacts (See CCSP 2009b). Accurate understanding of transportation impacts is specific to particular infrastructure elements, so detailed inventories of local and regional infrastructure must be combined with detailed and accurate elevation data and the best available predictions of local sea level rise and storm surge. Therefore, national assessments of sea level rise must be built on detailed local and regional assessments. Improved modeling is needed on the interaction between sea level rise, storm surge, tidal movement and wave action to get a better understanding of the dynamics of the phenomenon.
Assessment of confidence based on evidence	The authors have high confidence that sea levels are rising and that storm surge on top of these higher sea levels pose risks to coastal transportation, based

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 5: Transportation

Key Message Process: See key message #1.

Key message #3/4	**Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.**
Description of evidence base	The key message and supporting text summarize extensive evidence documented in "Climate Impacts and U.S. Transportation (DOT 2012)". Technical Input reports (21) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Specific regional climate impacts can be identified in each NCA region of the country. Specific climate impacts on transportation by region include: In Alaska, rising temperatures cause permafrost to melt, causing damage to roadbeds, airfields, pipelines, and other transportation infrastructure (Adaptation Advisory Committee 2010) In the Northeast, the Chesapeake region is likely to experience particularly severe local sea level rise due to geologic subsidence (CCSP 2009b), and increased precipitation generally (see Ch. 2: Our Changing Climate, Key Message 5, and Ch.16: Northeast), along with an increased incidence of extreme weather events. The presence of large populations with associated transportation system in coastal areas increased the potential impacts of sea level rise, storm surge, and precipitation-induced flooding. The Southeast includes Virginia, so it shares the threat of regional sea level rise in the Chesapeake, as well as significant threat to transportation infrastructure of national significance in Louisiana (CCSP 2008), as well as the interacting effects of sea level rise and increased precipitation, and extreme events. Midwest transportation infrastructure is subject to changing water levels on the Great Lakes (Angel and Kunkel 2010) and barge traffic disruptions due to flooding or drought on the Mississippi/Missouri/Ohio river system, as might be induced by changes in precipitation patterns. In the Southwest, rail and highway systems may be exposed to increased heat damage from the higher temperatures. The key risk is that declining precipitation (see Ch. 2: Our Changing Climate, Key Message 5) may induce changes in the economy and society of the Southwest that will affect the transportation systems that serve this region. San Francisco Bay, which encompasses two major airports and numerous key transportation links, is at risk for sea level rise and storm surge (California Natural Resources Agency 2009). Much of the economy of the Northwest is built around electricity and irrigation from a network of dams. The performance of this system may be affected by changing precipitation patterns, with potential consequences for agriculture and industry, and, consequently for transportation systems. In addition, the Seattle area may be affected by sea level rise (Washington State University 2012) Many relevant and recent climate data and models predict more intense precipitation events in much of the U. S. especially the Great Plains, Midwest, Northeast, and Southeast with decreased precipitation in parts of the Southwest and Southeast (see Ch. 2: Our Changing Climate, Key Message 5).
New information and	New regional climate model data from CMIP5 will have a significant impact on

remaining uncertainties	regional impact assessments. Climate data desired by transportation planners may be different than the projections generated by regional climate models. This presents a number of challenges: Regional scale transportation impacts are often determined by flood risk and by water flows on rivers and streams. Flooding is, of course, linked to precipitation, but the linkage between precipitation and hydrology is very complex. Precipitation, as represented in climate models, is often difficult to reduce to predictions of future flooding, which is what infrastructure designers would like to have. Similarly, an ice storm would be an extreme event for a transportation planner, but the frequency of ice storms probably cannot be derived from climate models. More generally, improved methods of deriving the frequency infrastructure-affecting weather events from regional climate models may be helpful in assessing climate impacts on transportation systems. Recent data clearly show and climate models further substantiate an increase in the intensity of precipitation events throughout much of the U.S. There is a need for a better definition of the magnitude of increased storm intensity so that accurate return frequency curves can be established. There are uncertainties associated with the correlation between a warming climate and increased hurricane intensity. In regions likely to see decreased precipitation, especially those areas subject to drought, stronger correlations to fire threat and lowered water levels in major waterways are needed.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is high that extreme weather events will affect transportation in all areas of the country.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 5: Transportation

Key Message Process: See key message #1.

Key message #4/4	**Climate change impacts will increase costs to transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions.**
Description of evidence base	The economic cost of climate change to the transportation sector has been little studied. However, there is substantial evidence that costs will be significant A recent study of climate change in New York indicated that a storm surge severe enough to flood Manhattan tunnels might cost as much as $100 billion (Rosenzweig et al. 2011b) A study of the risk to specific infrastructure elements in Alaska (Larsen 2007) a estimated the net present value of the extra cost from climate change at $2-$4 billion through 2030, and $4-$8 billion through 2080. The indirect evidence for significant costs from climate change impacts begin with the consequences of recent hurricanes, particularly on the Eastern Seaboard, where Hurricane Irene, a rather minor storm, produced unexpectedly heavy infrastructure damage from heavy rains. The economic cost of infrastructure damage is often greater than the cost of repairing or replacing infrastructure. For example, when the I-35W bridge collapsed in 2007, the State of Minnesota estimated the economic cost of lost use at $0.4 million per day, while the replacement cost of the bridge was $234 million (Haugen 2008; Xie and Levinson 2011) In addition a recent study of on-road congestion estimates the annual cost of highway congestion at about $100 billion (Schrank et al. 2011) the Federal Highway Administration estimates that weather accounts for about 15 percent of total delay (Cambridge Systematics and Texas Transportation Institute 2005). Similarly, a recent study of aviation congestion indicates that the annual cost of airline delay is about $33 billion (Ball et al. 2010) and that weather accounts for more than a third of airline delays. There is a strong circumstantial case to be made that increased frequency of extreme events (as defined by climate scientists) will produce increase traffic and aviation delays. Given the scale of current costs, even small changes in delay can have substantial economic costs. There is little published material on transportation adaption costs and benefits in the literature, in part because "adaptation" is an abstraction. Climate change is statistical weather, and manifests itself as a change in the frequency of events that would still occur (but with lower frequency) in the absence of climate change. Transportation agencies decide to protect (or not) specific pieces of infrastructure based on a range of considerations, including age and condition, extent of current and future usage, and cost of protection, as well as changing weather patterns. The authors, however, are aware, that transportation systems have always been required to adapt to changing conditions, and that, in general, it is almost always far less expensive to protect useful infrastructure than to wait for it to collapse. This professional experience, based on examination of multitudes of individual engineering studies, is the basis for the conclusion in the report, There are numerous examples of actions taken by state and local governments to enhance resilience and reduce climate impact costs on transportation including land-use planning to discourage development in vulnerable areas, establishment of design guidelines to reduce vulnerability to sea level rise, use of effective stormwater management techniques and coordinated emergency response systems.
New information and	There is relatively little information on the costs of climate change in the transportation sector, and less on the benefits of adaptation. Much of the available

remaining uncertainties	research is focused on costs of replacing particular assets, with far less effort devoted to impacts of climate change on transportation systems. Calculating climate impact and adaptation costs and benefits is an exceptionally complex problem, particularly at high levels of aggregation, since both costs and benefits accrue based on a multitude of location specific events. In addition, all of the methodological issues that are confronted by any long-term forecasting exercise are present. The problem may be more manageable at the local and regional scales at which most transportation decisions are usually made.
Assessment of confidence based on evidence	The authors have high confidence that climate impacts will be costly to the transportation sector, but are far less confident in assessing the exact magnitude of costs, based on the available evidence and their experience. The authors also have high confidence, based upon their experience, that costs may be significantly reduced by adaptation action, though, as noted the magnitude of such potential reductions on a national scale would be difficult to determine.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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6. Agriculture

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Key Messages

1. **Climate disruptions to agricultural production have increased in the recent past and are projected to increase further over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.**
2. **Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change-induced stresses.**
3. **Current loss and degradation of critical agricultural soil and water assets by increasing extremes in precipitation will continue to challenge both rain-fed and irrigated agriculture unless innovative conservation methods are implemented.**
4. **The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.**
5. **Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with future climate change.**
6. **Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, not only through changes in crop yields, but also changes in the ways climate affects food processing, storage, transportation, and retailing.**

The United States produces nearly $300 billion per year in agricultural commodities, with the contributions from livestock accounting for roughly half of that value. Production of all commodities will be vulnerable to direct impacts from changing climate conditions on crop and livestock development and yield, and indirect impacts through increasing pressures from pests and pathogens that will benefit from a changing climate. Agriculture continually adapts to climate change through changes in crop rotations, planting times, genetic selection, water management, and shifts in areas of crop production. These have proven to be effective strategies to allow agricultural production to increase as evidenced by the continued increase in production and efficiency of production across the U.S.

Climate change poses a major challenge to U.S. agriculture, because of the critical dependence of the agricultural system on climate and because of the complex role agriculture plays in rural and national social and economic systems. Climate change has the potential to both positively and negatively affect the patterns and productivity of crop, livestock, and fishery systems at the local, national, and global scales. It will also alter the stability of food supplies and create new food security challenges for the United States as the world seeks to feed nine billion people by 2050. U.S. agriculture exists as part of the global economy and agricultural exports have outpaced imports as part of the overall balance of trade; however, climate change will affect the quantity of produce available for export and import as well as the prices.

The cumulative impacts of climate change will ultimately depend on changing global market conditions as well as responses to local climate stressors, including farmers adjusting planting patterns in response to altered crop yields, seed producers investing in drought-tolerant varieties, and nations restricting trade to protect food security. Adaptive actions in the areas of consumption, production, education, and research include seizing opportunities to increase profitability and minimizing threats posed by unfavorable conditions.

Increasing Impacts on Agriculture

Climate disruptions to agricultural production have increased in the recent past and are projected to increase further over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.

Strategies are available to producers for adapting to mean temperature and precipitation changes projected (Malcolm et al. 2012; Ch. 2: Our Changing Climate) for the next 25 years. Future changes in extremes are less well understood however, and increases could lead to disruption of national food production and prices. These strategies include continued technological advancements, expansion of irrigated acreage, regional shifts in crop acreage, other adjustments in inputs and outputs, and changes in livestock management practices caused by changing climate patterns (Adams et al. 1987; Darwin et al. 1995; Mendelsohn et al. 1994; Reilly et al. 2003; Rosenzweig and Parry 1994; Sands and Edmonds 2005). However, such projections often fail to consider the impacts from weeds, insects, and diseases that accompany changes in both trends and extremes, which can increase losses significantly (Malcolm et al. 2012). By mid-century, when temperature increases are projected to exceed 1.8°F to 5.4°F and precipitation extremes are further intensified, yields of major U.S. crops and farm profits are expected to decline (IPCC 2007; Ortiz et al. 2008; Schlenker et al. 2005). There have been detectable impacts on production already due to the increasing temperatures (Lobell et al. 2011). Climate change is expected to increase the annual variation in crop and livestock production because of its effects on weather patterns and because of increases in numbers of extreme weather events, resulting in more variation in production over time (Hatfield et al. 2011; Lobell and Gourdji 2012). The overall implications for production are for increased uncertainty in production totals, which affect both domestic and international markets and food prices. This will affect the potential for adequate food, feed, fiber, and fuel derived from agricultural production systems.

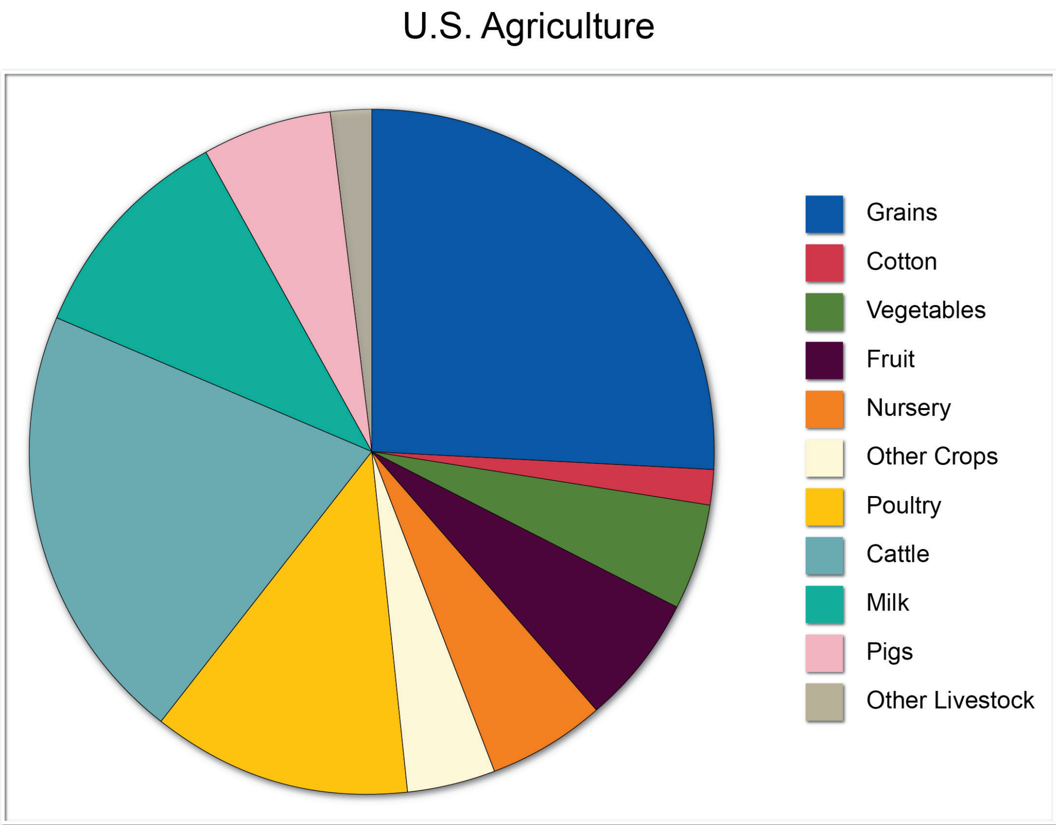

Figure 6.1: U.S. Agriculture

Caption: U.S. agriculture includes 300 different commodities with a nearly equal division between crop and livestock products. This chart shows a breakdown of U.S. agriculture products by category, based on the values of the respective products. (Data from 2007 Census of Agriculture, USDA National Agricultural Statistics Service, 2008)

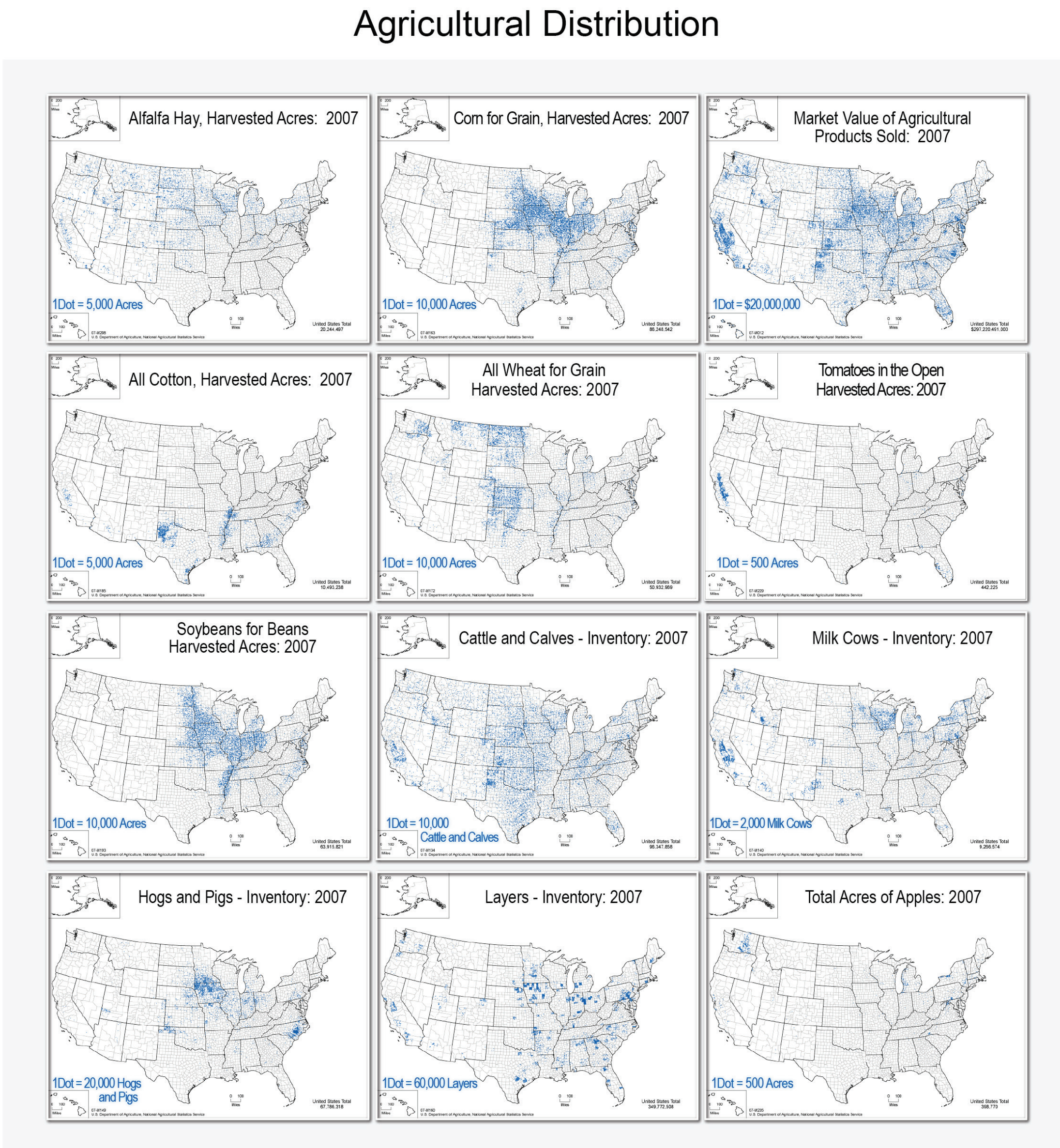

Figure 6.2: Agricultural Distribution

Caption: Agriculture is distributed across the United States with market value and crop types varying by region. In 2007, the total market value was nearly $300 billion dollars. The wide distribution of agricultural commodities across the U.S. is expected to result in differing effects of climate change on these commodities. (Source: 2007 Census of Agriculture, USDA National Agricultural Statistics Service, 2008)

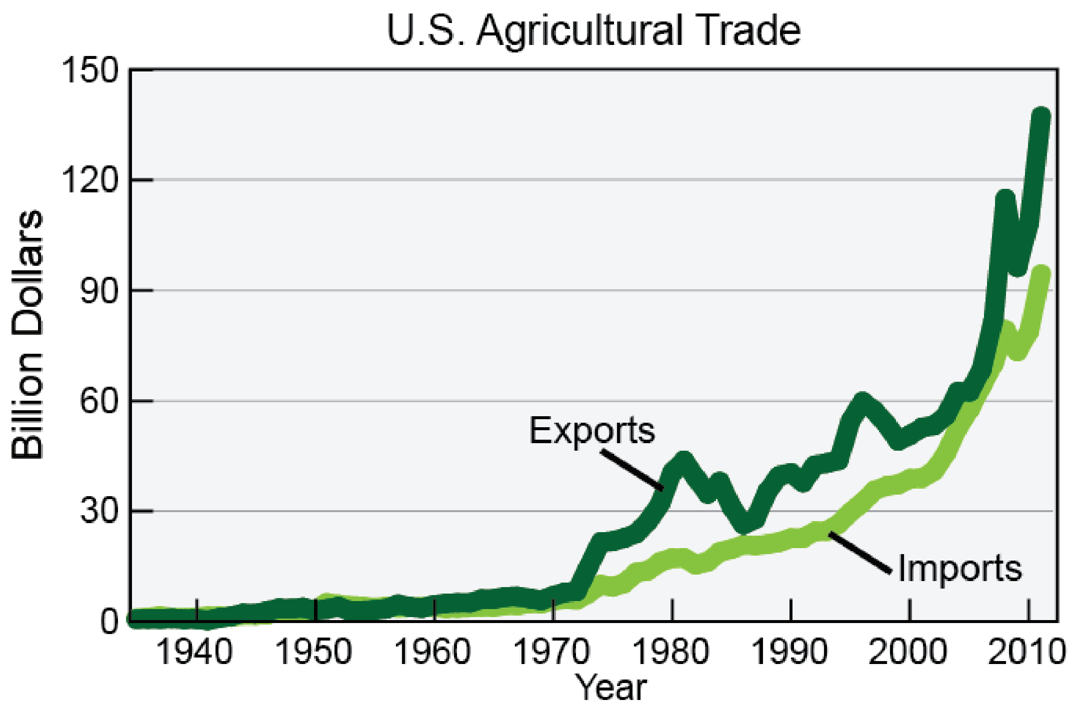

Figure 6.3: U.S. Agricultural Trade

Caption: U.S. agriculture exists in the context of global markets. Climate is among the important factors that affect these markets. For example, the increase in U.S. food exports in the 1970s is attributed to a combination of rising incomes in other nations, changes in national currency values and farm policies, and poor harvests in many nations in which climate was a factor. Through impacts on harvests and other impacts, climate change will continue to be a factor in global markets. (Data from USDA, Economic Research Service, 2012)

Plant response to climate change is dictated by complex interactions among carbon dioxide (CO_2), temperature, solar radiation, and precipitation. Each crop species has a given set of temperature thresholds that define the upper and lower boundaries for growth, along with an optimum temperature (Hatfield et al. 2011). Plants are currently grown in areas where temperatures match their thresholds. As temperatures increase over this century, crop production areas may shift to follow the temperature range for optimal growth and yield of grain or fruit. Temperature effects on crop production are only one component, and production over years in a given location is more affected by available soil water during the growing season than temperature (Hatfield et al. 2011; Walthall et al. 2012).

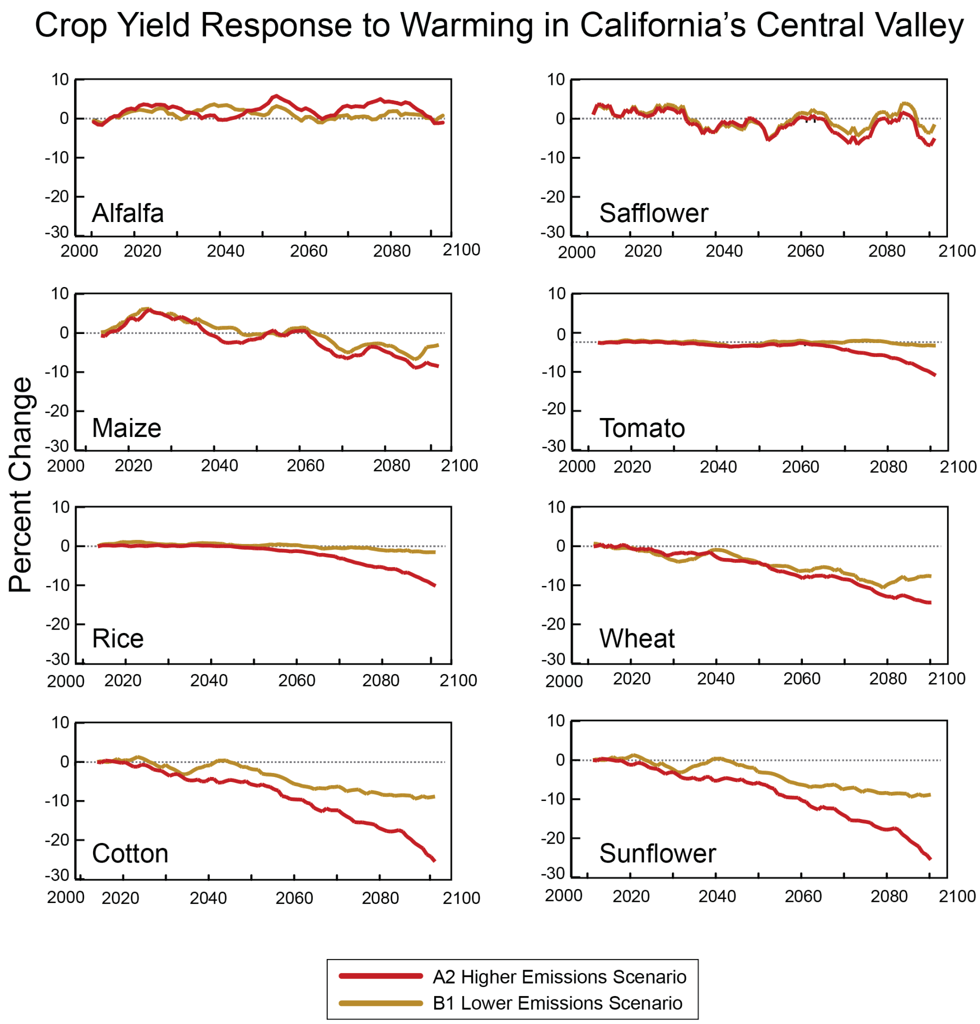

Figure 6.4: Crop Yield Response to Warming in California's Central Valley

Caption: Changes in climate through this century will affect crops differently because individual species respond differently to warming. Crop yield responses for eight crops in the central valley of California are projected under two emissions scenarios, one in which heat-trapping gas emissions are substantially reduced (B1, in gold) and another in which these emissions continue to grow (A2, in red). The crop model used in this analysis (DAYCENT) assumes that water supplies and nutrients are maintained at adequate levels. The lines show five-year moving averages for the period from 2000 to 2097 with the yield changes shown as differences from the 2000 baseline. Yield response varies among crops with alfalfa showing only year-to-year variation across the whole period, while cotton, maize, wheat, and sunflower begin to show yield declines early in the period. Rice and tomato do not show a yield response until the latter half of the period with the higher emissions scenario resulting in a larger yield response (Lee et al. 2011).

One critical period in which temperatures are a major factor is the pollination stage; pollen release triggers development of fruit, grain, or fiber. Exposure to high temperatures during this period can greatly reduce crop yields and increase the risk of total crop failure. Plants exposed to high nighttime temperatures during the grain, fiber, or fruit production period experience lower productivity and reduced quality (Walthall et al. 2012). These effects have already begun to occur; corn yields were affected by high nighttime temperatures in 2010 and 2012 across the Corn Belt, and with the number of nights with hot temperatures projected to increase as much as 30%, yield reductions will become more prevalent. (Hatfield 2012, personal communication; Hatfield et al. 2011; Ch. 2: Our Changing Climate).

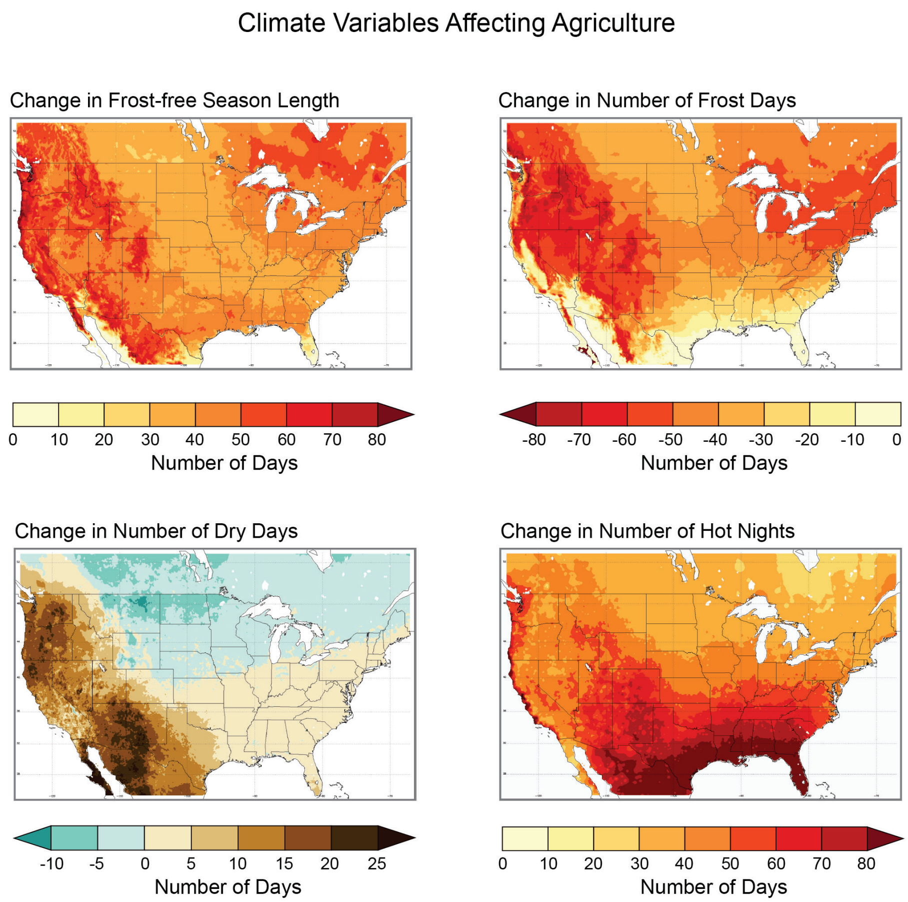

Figure 6.5: Climate Variables Affecting Agriculture

Caption: Many climate variables affect agriculture. Changes in climate parameters critical to agriculture show lengthening of the growing season and reductions in the number of frost days (days with minimum temperatures below freezing) for 2100, under an emissions scenario that assumes continued increases in heat-trapping gases (A2). Changes in these two variables are not identical, with the length of the growing season increasing across most of the U.S. and more variation in the change in the number of frost days. Warmer-season crops, such as melons, would grow better in warmer areas, while other crops, such as cereals, would grow more quickly, meaning less time for the grain itself to mature, reducing productivity (Hatfield et al. 2011). Taking advantage of the increasing length of the growing season and changing planting dates could allow planting of more diverse crop rotations, which can be an effective adaptation strategy. In the lower, right graph, hot nights are defined as nights with a minimum temperature warmer than 90% of the minimum temperatures between 1971 and 1990 (Source: Walthall et al. 2012).

Temperature and precipitation will be affected by an increase in both the number of consecutive dry days (less frequent precipitation events) and the number of hot nights. The western and southern parts of the nation show the greatest projected increases in consecutive dry days, while the number of hot nights is projected to increase throughout the U.S. These increases in consecutive dry days and hot nights will have negative impacts on efficient crop and animal production. High nighttime temperatures during the grain-filling period (the period between the fertilization of the ovule and the production of a mature seed in a plant) increase the rate of grain-filling and decrease the length of the grain-filling period, resulting in reduced grain yields. A similar response is found in animals in which exposure to multiple hot nights increases the degree of stress imposed on the animal (Mader 2012).

Increasing temperatures cause cultivated plants to grow and mature more quickly, causing plants to be smaller because soil may not be able to supply nutrients at required rates, thereby reducing growth and reducing grain, forage, fruit, or fiber production. Reduction in solar radiation in agricultural areas in the last 60 years (Qian et al. 2007) is projected to continue (Pan et al. 2004). Decreases in solar radiation may partially offset the acceleration of plant growth due to higher temperature and CO_2 depending on the crop. In vegetables, exposure to temperatures in the range of 1.8°F to 7.2°F above optimal moderately reduces yield, and exposure to temperatures more than 9°F to 12.6°F above optimal often leads to severe if not total production losses. Selective breeding for both plants and animals provides some opportunity for adapting to climate change; however, development of new varieties in perennial specialty crops commonly requires 15 to 30, or more, years, greatly limiting adaptive opportunity unless varieties could be introduced from other areas.

A warmer climate will impact growing conditions in many ways. For example, perennial specialty crops have a winter chilling requirement (typically expressed as hours when temperatures are between 32°F and 50°F) ranging from 200 to 2,000 cumulative hours. Yields decline if the chilling requirement is not completely satisfied, because flower emergence and viability is low. Chilling requirements for fruit and nut trees in California are projected to not be met by the middle to the end of this century (Luedeling et al. 2009). For most of the Northeast, a 400-hour chilling requirement is projected to continue to be met during this century, but crops (such as cherries) with prolonged chilling requirements (1,000 or more hours) could be negatively affected, particularly in southern parts of the Northeast (Wolfe et al. 2008). Warmer winters can lead to early bud-burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring (Walthall et al. 2012), as was the case with cherries in Michigan in 2012 (Andresen 2012, personal communication).

Many Plants Need Chilling to Produce Fruit — Reduced Chilling is Projected

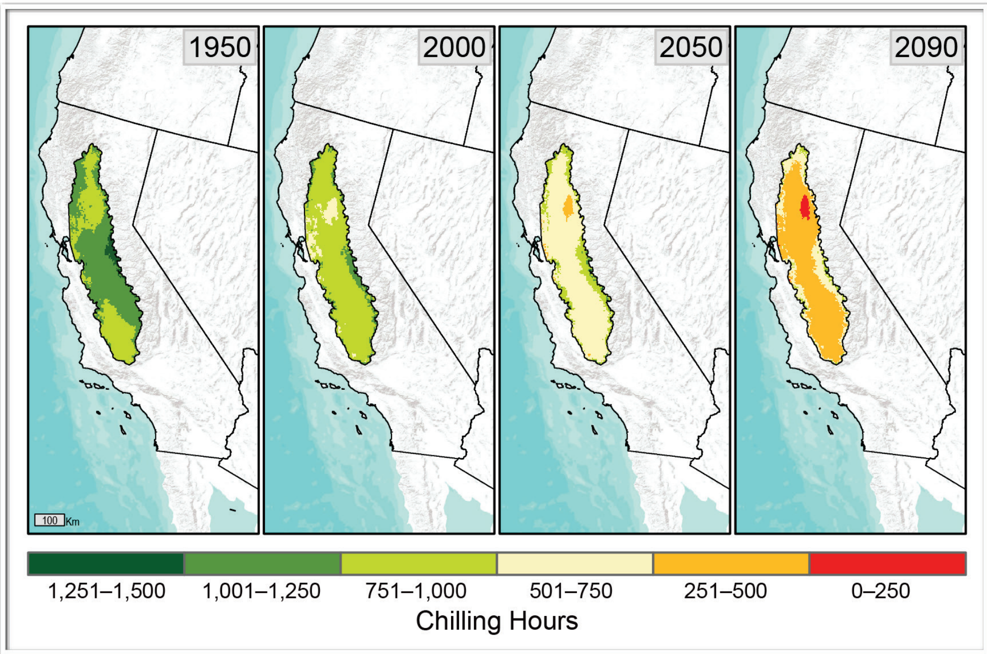

Figure 6.6: Many Plants Need Chilling to Produce Fruit – Reduced Chilling is Projected

Caption: Many perennial plants (fruit trees, grape vines) require exposure to particular numbers of chilling hours (hours in which the temperatures are below a given value over the winter). These values vary among species, and many trees require chilling hours before flowering and fruit set can occur. With rising temperatures, chilling hours will be reduced. One example of this change is shown here for California's Central Valley assuming that observed climate trends in that area continue through 2050 and 2090. Under such a scenario, a rapid decrease in the number of chilling hours is projected to occur over the next 100 years.

By 2000, the number of chilling hours in some regions was 30% lower than in 1950. Based on the A2 emissions scenario that assumes continued increases in heat-trapping gases, relative to 1950, the number of chilling hours is projected to decline by 30% to 60% by 2050 and by up to 80% by 2100. These are very conservative estimates of the reductions in chilling hours because climate models project *increasing* temperature trends rather than simply continuations of observed trends as assumed here. To adapt to these kinds of changes, trees with a lower chilling requirement would have to be planted or chemical manipulation would be required to induce chilling.

Various trees and grape vines differ in their chilling requirements, with grapes requiring 90 hours, peaches 225, apples 400, and cherries above 1,000 (Source: Luedeling et al. 2009).

Experiments have documented that elevated CO_2 concentrations can increase plant growth while increasing water use efficiency; however, the impacts of elevated CO_2 on grain and fruit yield and quality are mixed (Akin et al. 1987; Craine et al. 2010; Dijkstra et al. 2010; Gentile et al. 2012; Henderson and Robinson 1982; Morgan et al. 2008; Newman et al. 2005). Reduced nitrogen and protein content are observed in some plants such as soybean and alfalfa, causing a reduction in grain and forage quality, and reducing the ability of pasture and rangeland to support grazing livestock. The magnitude of CO_2 growth stimulation in the absence of other stressors has been extensively analyzed for crop and tree species (Ainsworth et al. 2002; Kimball 1983, 2011; Ziska 2003) and is relatively well understood; however, the interaction with changing temperature and water and nutrient constraints creates uncertainty in the magnitude of these responses (Sardans and Peñuelas 2012). Because the growth stimulation effect of CO_2 has a disproportionately positive impact on several weed species, this effect will contribute to increased risk of crop loss due to weed pressure (Ziska 2003, 2009).

The advantage of increased water use efficiency due to elevated CO_2 in areas with limited precipitation may be offset by other impacts from climate change. Rising average temperatures, for instance, will increase crop water demand, increasing the rate of water use by the crop. Increasing temperatures coupled with more extreme wet and dry events, or seasonal shifts in precipitation, will affect both crop water demand and plant production.

Animal agriculture is a major component of the U.S. agriculture system. Changing climatic conditions affect animal agriculture in four primary ways: 1) feed-grain production, availability, and price; 2) pastures and forage crop production and quality; 3) animal health, growth, and reproduction; and 4) disease and pest distributions (Rötter and Van de Geijn 1999). The optimal environmental conditions for livestock production include temperatures and other conditions for which animals do not need to significantly alter behavior or physiological functions to maintain relatively constant core body temperature. Optimum animal core body temperature is often maintained within a 4°F to 5°F range, while deviations from this range can cause disruptions in performance, production, and fertility that limit ability to produce meat, milk, or eggs. In many species, deviations in core body temperature in excess of 4°F to 5°F cause significant reductions in productive performance, while deviations of 9°F to 12.6°F often result in death (Gaughan et al. 2009). For cattle that breed during spring and summer, exposure to high temperatures reduces conception rates. Livestock and dairy production is more affected by the number of days of extreme heat than by increases in average temperature (Mader 2003). Elevated humidity exacerbates the impact of high temperatures on animal health and performance.

Animal Response to Temperature Extremes

Animals respond to extreme temperature events (hot or cold) by altering their metabolic rates and behavior. Increases in extreme temperature events may become more likely for animals, placing them under conditions where their efficiency in meat, milk, or egg production is impacted. Projected increases in extreme heat events (Ch. 2: Our Changing Climate, Key Message 7) will further increase the stress on animals, leading to the potential for greater impacts on production (Mader 2003). Meat animals are managed for a high rate of weight gain (high metabolic rate), which increases their potential risk when exposed to high temperature conditions. Exposure to heat stress causes problems for animals and alters their internal temperature when exposure occurs. Exposure to high temperature events can be costly to producers, as was the case in 2011, when heat-related production losses exceeded $1 billion dollars (NOAA 2012).

Livestock production systems that provide partial or total shelter to reduce thermal environmental challenges can reduce the risk and vulnerability associated with extreme heat. In general, livestock such as poultry and swine are managed in housed systems where airflow can be controlled and housing temperature modified to minimize or buffer against adverse environmental conditions. However, management and energy costs associated with increased temperature regulation will increase for confined production enterprises and may require modification of shelter and increased water use for cooling.

Weeds, Diseases, and Pests

Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change-induced stresses.

Several weeds benefit more than crops from higher temperatures and CO_2 levels (Ziska 2003, 2009). One concern involves the northward spread of invasive weeds like privet and kudzu, which are already present in the South (Bradley et al. 2010). Controlling weeds costs the U.S. more than $11 billion a year, with most of that spent on herbicides. Both herbicide use and costs are expected to increase as temperatures and CO_2 levels rise. Also, the most widely used herbicide in the U.S., glyphosate (also known as RoundUp™ and other brand names), loses its efficacy on weeds grown at CO_2 levels projected to occur in the coming decades (Ziska et al. 1999). Higher concentrations of the chemical and more frequent sprayings thus will be needed, increasing economic and environmental costs associated with chemical use.

A warmer world brings higher humidity in wet years. This helps insects and diseases flourish, with negative indirect impacts on animal health and productivity (De Lucia et al. 2012; Garrett et al. 2006; Garrett et al. 2011; Jamieson et al. 2012; Wu et al. 2011). Climate affects microbial populations and distribution, the distribution of diseases carried by insects and rodents, animal and plant resistance to infections, food and water shortages, and food-borne diseases (Baylis and Githeko 2006; Gaughan et al. 2009; Thornton 2010). Earlier spring and warmer winter conditions may increase survival and proliferation of disease-causing agents and parasites. Regional warming and changes in rainfall distribution may change the distributions of diseases that are sensitive to temperature and moisture, such as anthrax, blackleg, and hemorrhagic septicemia, and lead to increased incidence of ketosis, mastitis, and lameness in dairy cows (Baylis and Githeko 2006; Gaughan et al. 2009).

Extreme Precipitation

Current loss and degradation of critical agricultural soil and water assets by increasing extremes in precipitation will continue to challenge both rain-fed and irrigated agriculture unless innovative conservation methods are implemented.

Soil and water are essential resources for agricultural production, and both are subject to new conditions as climate changes. Precipitation and temperature affect the *potential* amount of water available, but the *actual* amount of available water also depends on soil type, soil water holding capacity, and the rate at which water filters through the soil. Such soil characteristics, however, are sensitive to changing climate conditions; changes in soil carbon content and soil loss will be affected by direct climate effects through changes in soil temperature, soil water availability, and the amount of organic matter input from plants (Pan et al. 2010).

A few of the many important ecosystem services provided by soils include: the provision of food, wood, fiber such as cotton, and raw materials; flood mitigation; recycling of wastes; biological control of pests; regulation of carbon and other heat-trapping gases; physical support for roads and buildings; and cultural and aesthetic values (Dominati et al. 2010). Productive soils are characterized by levels of nutrients necessary for the production of healthy plants, moderately high levels of organic matter, a soil structure with good binding of the primary soil particles, moderate pH levels, thickness sufficient to store adequate water for plants, a healthy microbial community, and absence of elements or compounds in concentrations that are toxic for plant, animal, and microbial life.

Several processes act to degrade soils, however, including erosion, compaction, acidification, salinization, toxification, and net loss of organic matter. Several of these processes, particularly erosion, will be directly affected by climate change. Rainfall's erosive power is expected to increase as a result of increases in rainfall amount in northern portions of the U.S. (see Ch. 2: Our Changing Climate) accompanied by further increases in precipitation intensity (Favis-Mortlock et al. 1996; Favis-Mortlock and Guerra 1999; Nearing 2001; Pruski and Nearing 2002a, 2002b). Projected shifts in rainfall intensity that include more extreme events will increase soil erosion in the absence of conservation practices (Kunkel et al. 2012; Mass et al. 2010).

Box: It is All About the Water!
Soil is a critical component of agricultural systems, and the changing climate affects the amount, distribution, and intensity of precipitation. Soil erosion occurs when the rate of precipitation exceeds the ability of the soil to maintain an adequate infiltration rate. When this occurs, runoff from fields moves water and soil from the field into nearby water bodies.

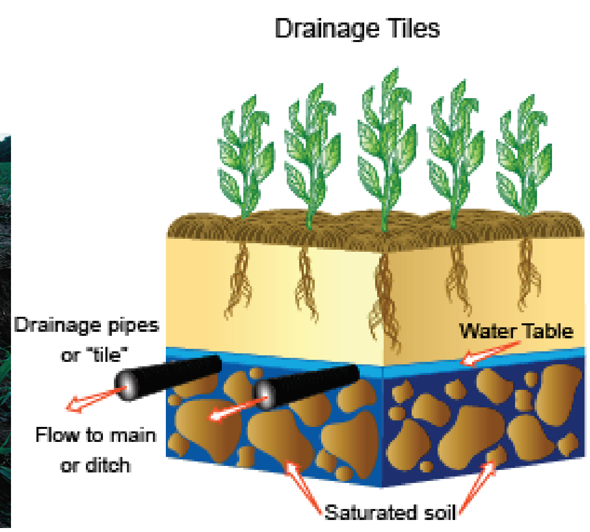

Figure 6.7 **Figure 6.8**

Water lost from the edge of the field is no longer available to the crop, and the soil that is removed is no longer in place to support crop growth. The increasing intensity of storms and the shifting of rainfall patterns toward more spring precipitation in the Midwest may lead to more scenes similar to this one. An analysis of the rainfall patterns across Iowa has shown there has not been an increase in total annual precipitation; however, there has been a large increase in the number of days with heavy rainfall. This has been coupled with an increase in spring precipitation, which has decreased the number of workable days in the April to May period in Iowa by 3 days compared to the period from 1980-2000. To offset this increased precipitation, producers have been installing subsurface drainage to remove more water from the fields. These are elaborate systems designed to move water from the landscape to allow agricultural operations to occur in the spring. Water erosion and runoff is only one portion of the spectrum of extreme precipitation. The potential for wind erosion, for example, could be increased in areas with persistent drought because of the reduction in vegetative cover and in many areas will increase erosion.

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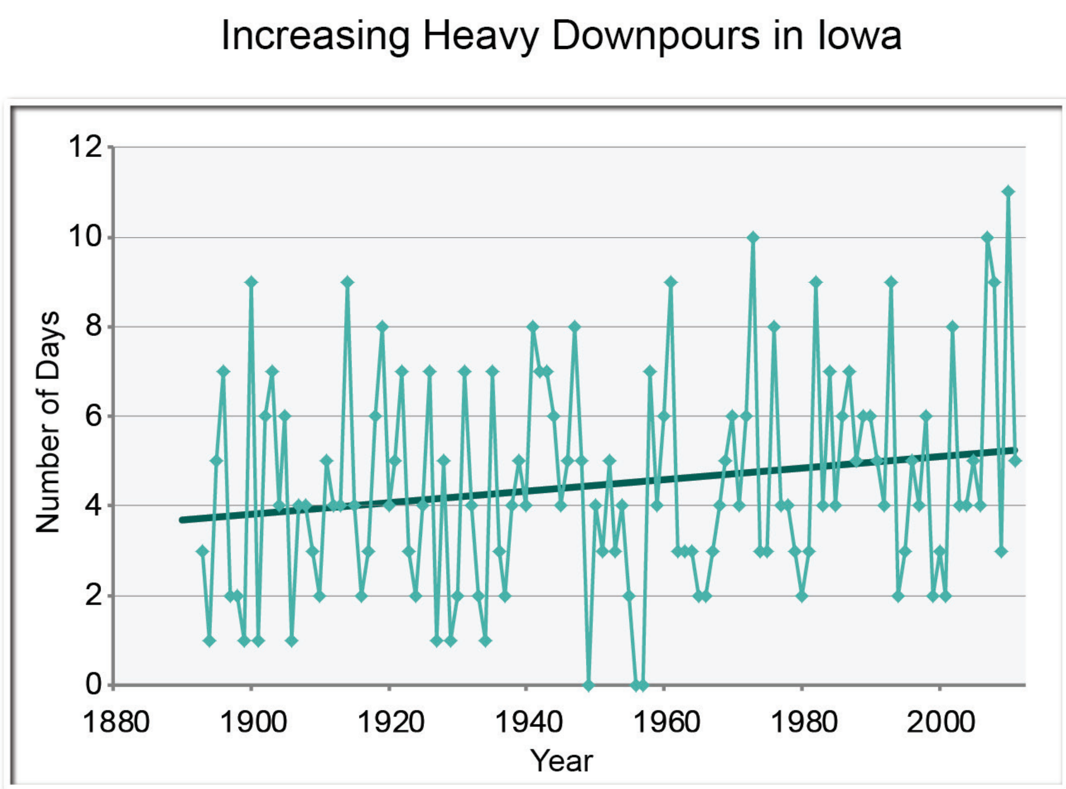

Figure 6.9: Increasing Heavy Downpours in Iowa

Caption: Iowa is the nation's top corn and soybean producing state. These crops are planted in the spring. Heavy rain can delay planting and create problems in obtaining a good stand of plants, both of which can reduce crop productivity. In Iowa soils with even modest slopes, more than 1.25 inches of rain in a single day leads to runoff that causes soil erosion and loss of nutrients, and under some circumstances can lead to flooding. The graph shows the number of days per year during which more than 1.25 inches of rain fell in Des Moines, Iowa. The upward trend is evident, with many recent years having more than 8 days with such heavy rainfall, which used to be rare. (Data from NWS Cooperative Observer Program, 2012)

Changes in production practices can have more effect than climate change on soil erosion. Though uncertainty is high, studies have shown that a reduction in projected crop biomass (and hence the amount of crop residue that remains on the surface over the winter) will increase soil loss (O'Neal et al. 2005; Wischmeier and Smith 1978). Expected increases in soil erosion under climate change also will lead to increased off-site, non-point-source pollution. Soil conservation practices will therefore be an important element of agricultural adaptation to climate change (Delgado et al. 2011).

Rising temperatures and shifting precipitation patterns will alter crop-water requirements, crop-water availability, crop productivity, and costs of water access across the agricultural landscape. Higher temperatures are projected to increase both evaporative losses from land and water surfaces and transpiration losses (through plant leaves) from non-crop land cover, potentially reducing annual runoff and streamflow for a given amount of precipitation. The resulting shift in crop competitiveness, in turn, will drive changes in cropland allocations and production systems.

Heat and Drought

The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.

Climate change projections suggest an increase in extreme heat, severe drought, and heavy precipitation (Peterson et al. 2012). Extreme climate conditions, such as dry spells, sustained droughts, and heat waves all have large effects on crops and livestock. The timing of extreme events will be critical because they may occur at sensitive stages in the life cycles of agricultural crops or reproductive stages for animals. Extreme events at vulnerable times could result in major impacts on growth or productivity, like hot-temperature extreme weather events on corn during pollination. Recent studies suggest that, with increased average temperature, during times of future droughts the higher temperatures and dry conditions will amplify drought severity and temperature extremes (Alexander et al. 2006; IPCC 2007; Karl et al. 2012; Zhang et al. 2007).

The occurrence of very hot nights and the duration of periods lacking agriculturally significant rainfall are projected to increase by the end of this century.

Crops and livestock will be at increased risk of exposure to extreme heat events. Projected increases in the occurrence of extreme heat events will expose production systems to conditions exceeding maximum thresholds for given species more frequently. Goats, sheep, beef cattle, and dairy cattle are the livestock species most widely managed in extensive outdoor facilities. Within physiological limits, animals can adapt to and cope with gradual thermal changes, though shifts in thermoregulation may result in a loss of productivity (Gaughan et al. 2002a; Gaughan et al. 2002b; Mader et al. 2007). Lack of prior conditioning to rapidly changing or adverse weather events, however, often results in catastrophic deaths in domestic livestock and losses of productivity in surviving animals (Mader 2003).

Rate of Adaptation

Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with future climate change.

Adaptation strategies currently used by U.S. farmers to cope with weather and climate changes include changing selection of crops, the timing of field operations, and the increasing use of pesticides to control increased pressure from pests. Technological innovation increases the tools available to farmers in some agricultural sectors. Diversifying crop rotations, integrating livestock with crop production systems, improving soil quality, minimizing off-farm flows of nutrients and pesticides, and other practices typically associated with sustainable agriculture also increase the resiliency of the agricultural system to productivity impacts of climate change (Easterling 2010; Lin 2011; Tomich et al. 2011; Wall and Smit 2005). In the Midwest, there have been shifts in the distribution of crops partially related to the increased demand for biofuels (USDA-NASS 2012; See also Ch. 10: Water, Energy, and Land Use for more discussion on biofuels). In California's Central Valley, an adaptation plan consisting of integrated changes in crop mix, irrigation methods, fertilization practices, tillage practices, and land management may be an effective approach to managing climate risk (Jackson et al. 2009). These practices are available to all agricultural regions of the U.S. as potential adaptation strategies.

Based on projected climate change impacts in some areas of the United States, agricultural systems may have to undergo more transformative changes to remain productive and profitable in the long-term (Easterling 2010). Research and development of sustainable natural resource management strategies inform adaptation options for U.S. agriculture. More transformative adaptive strategies, such as conversion to integrated crop-livestock farming, may reduce environmental impacts, improve profitability and sustainability, and enhance ecological resilience to climate change in U.S. livestock production systems (Izaurralde et al. 2011).

While there are many possible adaptive responses to climate change, potential constraints to adaptation must be recognized and addressed. In addition to regional constraints on the availability of critical basic resources such as land and water, there are potential constraints related to farm financing and credit availability in the U.S. and elsewhere. Research suggests that such constraints may be significant, especially for small family farms with little available capital (Antle et al. 2004; Knutson et al. 2011; Wolfe et al. 2008). In addition to the technical and financial ability to adapt to changing average conditions, farm resilience to climate change is also a function of financial capacity to withstand increasing variability in production and returns, including catastrophic loss (Beach et al. 2009; Smit and Skinner 2002). As climate change intensifies, "climate risk" from more frequent and intense weather events will add to the risks commonly managed by producers, such as those related to production, marketing, finances, regulation, and personal health and safety factors (Harwood et al. 1999; Howden et al. 2007). The role of innovative management techniques and government policies as well as research and insurance programs will have a substantial impact on the degree to which the agricultural sector increases climate resilience in the longer term.

Modern agriculture has continually adapted to many changing factors, both within and outside of agricultural systems. As a result, agriculture in the U.S. over the past century has steadily increased productivity and integration into world markets. Although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture. In the short term, existing and evolving adaptation strategies will provide substantial adaptive capacity, protecting domestic producers and consumers from many of the impacts of climate change, except possibly the occurrence of protracted extreme events. In the longer term, adaptation will be more difficult and costly because the physiological limits of plant and animal species will be exceeded more frequently, and the productivity of crop and livestock systems will become less reliable.

Food Security

Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, not only through changes in crop yields, but also changes in the ways climate affects food processing, storage, transportation, and retailing.

Climate change impacts on agriculture will have consequences for food security both in the U.S. and globally. Food security includes four components: availability, stability, access, and utilization of food (FAO 2001). Following this definition, in 2011, 14.9% of U.S. households did not have secure food supplies at some point during the year, with 5.7% of U.S. households experiencing very low food security (Coleman-Jensen et al. 2012). Food security is affected by a variety of supply and demand-side pressures, including economic conditions, globalization of markets, safety and quality of food, land-use change, demographic change, and disease and poverty (Ericksen et al. 2009; Misselhorn et al. 2012).

Within the complex global food system, climate change is expected to impact food security in multiple ways. In addition to changes in agricultural yields, projected rising temperatures, changing weather patterns, and increases in frequency of extreme weather events will impact distribution of food- and waterborne diseases as well as food trade and distribution (Schmidhuber and Tubiello 2007; Tirado et al. 2010). This means that U.S. food security depends not only on how climate affects crop yields at the local and national level, but also on how climate extremes and changes affect food processing, storage, transportation, and retailing, as well as the ability of consumers to purchase food. And because about one fifth of all food consumed in the U.S. is imported, our food supply and security can be significantly affected by climate variations and changes in other parts of the world. The import share has increased over the last two decades, and the U.S. now imports 13% of grains, 20% of vegetables (much higher in winter months), almost 40% of fruit, 85% of fish and shellfish, and almost all tropical products such as coffee, tea, and bananas (USDA 2012). Climate extremes in regions that supply these products to the U.S. can cause sharp reductions in production and increases in prices.

In an increasingly globalized food system with volatile food prices, climate events abroad may impact food security in the U.S. while climate events in the U.S. may impact food security globally. The globalized food system can buffer the local impacts of weather events on food security, but can also increase the global vulnerability of food security by transmitting shocks globally (Godfray et al. 2010).

The connections of U.S. agriculture and food security to global conditions are clearly illustrated by the recent food price spikes in 2008 and 2011 that highlighted the complex connections of climate, land use, demand, and markets. The doubling of the FAO food price index over just a few months was caused partly by weather conditions in food-exporting countries such as Australia, Russia, and the U.S., but was also driven by increased demand for meat and dairy in Asia, increased energy costs and demand for biofuels, and commodity speculation in financial markets (FAO 2011).

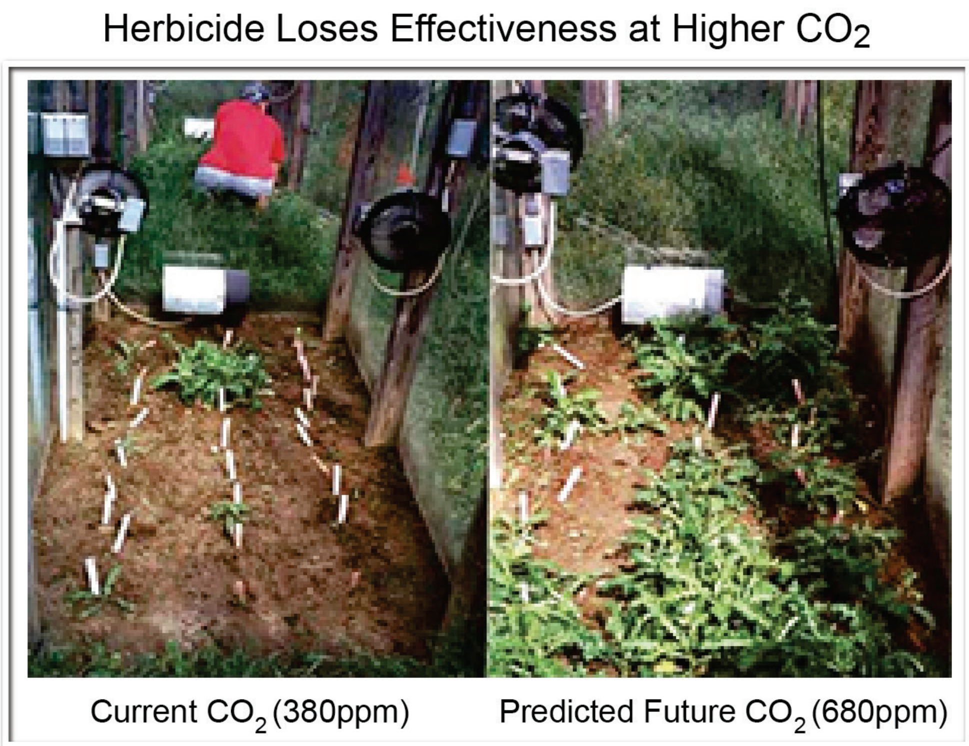

Figure 6.10: Herbicide Loses Effectiveness at Higher CO_2

Caption: The left photo shows weeds in a plot grown at a carbon dioxide (CO_2) concentration of about 380 parts per million (ppm), which approximates the current level of about 390 ppm. The right photo shows a plot in which the CO_2 level has been raised to about 680 ppm. Both plots were equally treated with herbicide (Wolfe et al. 2008). Photo credit: Lewis Ziska, USDA ARS.

Traceable Accounts

Key Message Process: A central component of the process was the development of a foundational technical input report (TIR), "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation" (Walthall et al. 2012). A public session conducted as part of the Tri-Societies (https://www.acsmeetings.org/home) meeting held in San Antonio, TX on Oct. 16-19, 2011, provided input to this report, as did numerous technical teleconferences among the TIR authors.

The report team engaged in multiple technical discussions via teleconference, which included careful review of the foundational TIR (Walthall et al. 2012) and of approximately 55 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the lead author of each message.

Key message #1/6	**Climate disruptions to agricultural production have increased in the recent past and are projected to increase further over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation (Walthall et al. 2012). Technical Input reports (55) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence that climate change will have impacts on crops and livestock is based on numerous studies and is incontrovertible (IPCC 2007; Lobell et al. 2011; Ortiz et al. 2008; Schlenker et al. 2005). The literature strongly suggests that carbon dioxide, temperature, and precipitation affect livestock and crop production. Plants have an optimal temperature range to which they are adapted and regional crop growth will be affected by shifts in that region's temperatures relative to each crop's optimal range. Large shifts in temperature can significantly impact seasonal biomass growth, while changes in the timing and intensity of extreme temperature effects are expected to negatively impact crop development during critical windows such as pollination. Crop production will also be impacted by changing patterns of seasonal precipitation; extreme precipitation events are expected to occur more frequently and negatively impact production levels. Livestock production is directly affected by extreme temperature as the animal makes metabolic adjustments to cope with heat stress (Walthall et al. 2012). Further production costs in confined systems markedly increase when heat abatement strategies and climate regulation are necessary.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Synthesis and Assessment Product 4.3, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States): http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products (Backlund et al. 2009). There is insufficient understanding of the interactions of rising carbon dioxide, changing temperatures and more variable precipitation patterns on crop production (Hatfield et al. 2011). The combined effects on plant water demand and soil water availability will be critical to understanding regional crop

	response. The role of increasing minimum temperatures on water demand and growth and senescence rates of plants is an important factor. There is insufficient understanding on how prolonged exposure of livestock to high or cold temperatures affect metabolism and reproductive variables (Craine et al. 2010). For grazing animals, there is a critical interaction with feed availability and quality on rangeland and pastureland that is determined by climate conditions during the growing season (Izaurralde et al. 2011). The information base can be enhanced by evaluating crop growth and livestock production models to enhance the understanding of the interactions of climate variables and the biological system. Better understanding of projected changes in precipitation will narrow uncertainty in future yield reductions (Hatfield et al. 2011; Izaurralde et al. 2011).
Assessment of confidence based on evidence	There are a range of controlled environment and field studies that provide the evidence for these findings. Confidence in this key message is therefore judged to be **high**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #2/6	**Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change-induced stresses.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation" (Walthall et al. 2012). Technical Input reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe the direct effect of climate on the ecological systems within which crop and livestock operations occur. Many weeds respond more strongly to CO_2 than do crops, and it is believed that the range of many diseases and pests (for both crop and livestock) will expand under warming conditions (Ziska 2001). Pests may have increased overwinter survival and fit more generations into a single year, which may also facilitate faster evolution of pesticide resistance. Changing patterns of pressure from weeds, other pests, and disease can impact crop and livestock production in ways that may be costly or challenging to address (Hatfield et al. 2011; Walthall et al. 2012).
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Backlund et al. 2009; Janetos et al. 2008) Improved models and observational data related to how many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change-induced stresses. A key issue is the extent of the interaction between components of the natural biological system (e.g., pests) and the economic biological system (e.g., crop or animal). For insects, increased populations are a factor; however, their effect on the plant may be dependent upon the phenological stage of the plant when the insect is at specific phenological stages (Walthall et al. 2012). To enhance our understanding of these issues will require a concerted effort to begin to quantify the interactions of pests and the economic crop or livestock system and how each system and their interactions are affected by climate (Walthall et al. 2012).
Assessment of confidence based on evidence	The scientific literature is beginning to emerge; however, there are still some unknowns about the effects of biotic stresses, and there may well be emergent "surprises" resulting from departures from past ecological equilibria. Confidence is therefore judged to be **medium** that many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change-induced stresses.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 6: Agriculture

Key Message Process: See Key Message #1.

Key message #3/6	**Current loss and degradation of critical agricultural soil and water assets by increasing extremes in precipitation will continue to challenge both rain-fed and irrigated agriculture unless innovative conservation methods are implemented.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation" (Walthall et al. 2012). Technical Input reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Soil erosion is affected by rainfall intensity and there is evidence of increasing intensity in rainfall events even where the annual mean is reduced (Pan et al. 2010). Unprotected soil surfaces will have increased erosion and require more intense conservation practices (Delgado et al. 2011; Wischmeier and Smith 1978). Shifts in seasonality and type of precipitation will affect both timing and impact of water availability for both rain-fed and irrigated agriculture. Evidence is strong that in the future there will be more precipitation globally, and that rain events will be more intense even if separated by longer periods without rain (IPCC 2007).
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Synthesis and Assessment Product 4.3, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States): http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products (Backlund et al. 2009). Improved models and observational data related to how current loss and degradation of critical agricultural soil and water assets by increasing extremes in precipitation will continue to challenge both rain-fed and irrigated agriculture. Precipitation shifts are the most difficult to project, and uncertainty in regional projections increases with time into the future (Alexander et al. 2006). To improve these projections will require enhanced understanding of shifts in timing, intensity, and magnitude of precipitation events. "The projected changes in the northern U.S. are a direct consequence of a warmer atmosphere. Warmer air can be moister than colder air, leading to more frequent and severe winter and spring storms. The projected reduction in Southwest precipitation is an indirect result of changes in atmospheric circulation caused by the global changes in climate. Recent improvements in the understanding of these mechanisms of change increase confidence in these projections" (see Ch. 2: Our Changing Climate).
Assessment of confidence based on evidence	The precipitation forecasts are the limiting factor in these assessments, the evidence of the impact on soil water availability and soil erosion are well-established. Confidence in this key message is therefore judged to be **high**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See Key Message #1.

Key message #4/6	**The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation" (Walthall et al. 2012). Technical Input reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe evidence that the occurrence of extreme events is increasing and exposure of plants or animals to temperatures and soil water conditions (drought, water-logged, flood) outside of the biological range for the given species will cause stress and reduce production. Direct effects of extreme events will be dependent upon the timing of the event relative to the growth stage of the biological system.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Agriculture assessment (Synthesis and Assessment Product 4.3, "The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States"): http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products (Backlund et al. 2009). One key area of uncertainty is the timing of the extreme events during the phenological stage of the plant or the growth cycle of the animal. For example, plants are more sensitive to extreme high temperatures during the pollination stage compared to vegetative growth stages (Hatfield et al. 2011). A similar response for animals is exposure to high temperatures during the conception phase (Mader 2003). Milk and egg production are also vulnerable to temperature extremes. Extreme combinations of weather variables must be considered, such as elevated humidity in concert with high temperatures (Mader 2003). Other key uncertainties include adequate precision in simulations of: the timing of extreme events relative to short time periods of crop vulnerability and the temperatures close to key thresholds such as freezing (Wolfe et al. 2008). The uncertainty is amplified by the rarity of extreme events. However, a shift of the distribution of temperatures can increase the frequency of threshold exceedance (Walthall et al. 2012). The information base can be enhanced by improving the forecast of extreme events, since the effect of extreme events on plants or animals is known (Adams et al. 1987; Alexander et al. 2006).
Assessment of confidence based on evidence	There is **high** confidence in the effects of extreme temperature events on crops and livestock, and the agreement in the literature is good.

CONFIDENCE LEVEL			
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Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See Key Message #1.

Key message #5/6	Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with future climate change.
Description of evidence base	There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies (Antle et al. 2004). Much of the economic literature suggests that in the short-term producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices, for the case of crop production (Antle et al. 2004). In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both. New strategies for building long-term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation (Malcolm et al. 2012). Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well-understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well-understood, either in the short or long term (Walthall et al. 2012). Adaptation may also be limited by availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production.
New information and remaining uncertainties	It is difficult to fully represent the complex interactions of the entire socio-ecological system within which agriculture operates to assess the relative effectiveness and feasibility of adaptation strategies at various levels. Economic impact assessments require improved understanding of adaptation capacity and agricultural resilience at the system level (including the agri-ecosystem impacts related to diseases and pests) and also improved understanding of adaptation opportunities, economic resilience, and constraints to adaptation at the producer level (Antle et al. 2004; Malcolm et al. 2012). The economic value of ecological services such as pollinator services is particularly difficult to quantify and incorporate into economic impact efforts (Walthall et al. 2012).
Assessment of confidence based on evidence	Emerging evidence about adaptation of agricultural systems to changing climate is beginning to be developed. The complex interactions among all of the system components presents a limitation to a complete understanding but does provide a comprehensive framework for the assessment of agricultural responses to climate change, providing **medium** confidence.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See Key Message #1.

Key message #6/6	**Climate change effects on agriculture will have consequences for food security both in the U.S. and globally, not only through changes in crop yields, but also changes in the ways climate affects food processing, storage, transportation, and retailing.**
Description of evidence base	Ongoing investigations conducted by the Food and Agriculture Organization (FAO 2008, 2011) as well as the U.S. Department of Agriculture (ERS 2012) and the National Research Council (2007) have documented the relationships between agricultural productivity, climate change, and food security. There are many factors that affect food security, and agricultural yields are only one of them. However, there is abundant evidence that changes in yield have impacts on prices and access to commodities both within the U.S. and across the globe (Liverman and Ingram 2010).
New information and remaining uncertainties	The components of food security derive from the intersection of political, physical, economic and social factors. In many ways the impact of climate change on crop yields is the least complex of the factors that affect the four components of food security (availability, stability, access and utilization). As the globalized food system is subject to conflicting pressures across scales, one approach to reducing risk is a "cross-scale problem-driven" approach to food security (Misselhorn et al. 2012). This and other approaches to understanding and responding to the complexities of the global food system need additional research.
Assessment of confidence based on evidence	There is **high** confidence that climate change impacts will have consequences for food security both in the U.S. and globally, and **very high** confidence that other related factors, including food processing, storage, transportation and retailing will also be affected by climate change

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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7. Forestry

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Key Messages

1. **Climate change is increasing the vulnerability of forests to ecosystem change and tree mortality through fire, insect infestations, drought, and disease outbreaks. Western U.S. forests are particularly vulnerable to increased wildfire and insect outbreaks; eastern forests have smaller disturbances but could be more sensitive to periodic drought.**
2. **U.S. forests currently absorb about 13% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake.**
3. **Bioenergy is an emerging new market for wood; with higher wood prices, development of a market in salvaged wood from trees killed by drought, insects, and fire could help finance salvage and restoration activities and reduce U.S. fossil fuel consumption. However, the environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.**
4. **The changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy will all influence forest management responses to climate change. However, development of and better access to practical and timely information for managers to consider in choosing adaptation and mitigation options will facilitate management of public and private forestland.**

Forests provide valuable commodities, like wood products, as well as benefits like recreational opportunities and lifestyle amenities that are more difficult to assess in monetary terms (Vose et al. 2012). Increasingly, forest managers, policymakers, and the public recognize that forests are valuable in many ways, providing everything from clean drinking water to wildlife habitat. This recognition has resulted in increased conservation management on both public and private land in recent decades.

In addition to these economic, social and ecological values, forests provide opportunities to reduce future climate change by capturing and storing carbon, as well as by providing resources for bioenergy production. The total amount of carbon stored in U.S. forest ecosystems and wood products equals roughly 25 years of U.S. heat-trapping gas emissions at current rates of emission, providing an important national "sink" that could grow or shrink depending on the extent of climate change, forest management practices, and other factors (EPA 2012; Woodall et al. 2011). For example, in 2010, U.S. forest ecosystems and the associated wood products industry captured and stored roughly 13% of all carbon dioxide emitted in the U.S. (EPA 2012). Forestland resources also have vast potential to produce bioenergy from 504 million acres of timberland and 91 million acres of other forestland (DOE 2011).

Economic considerations have historically influenced both the overall area of forestlands and their management, and will continue to do so. From 1700 to 1935, forests were extensively harvested for wood to use for heating and building materials and then converted to other uses, primarily for agriculture (Birdsey et al. 2006). This historic reduction in forest cover has partially reversed through forest regrowth on abandoned agricultural lands. However, conversion of forests to other uses, like urban expansion, continues (USFS 2012).

Today, private entities own 56% of the forestlands in the United States, primarily in the eastern states. The remaining 44% of forests are on public lands, primarily in the western U.S. Different challenges and opportunities exist for public and for private forest management decisions, especially when climate-related issues are considered on a national scale.

Forest health decline and an increase in forest disturbances on both public and private land are projected due to increases in wildfire, insects, disease, drought, and extreme events. At the same time, there is growing awareness that forests may play an expanded role in carbon management. Addressing climate change effects on forests requires considering the interactions among land-use practices, energy options, and climate change (Dale et al. 2011).

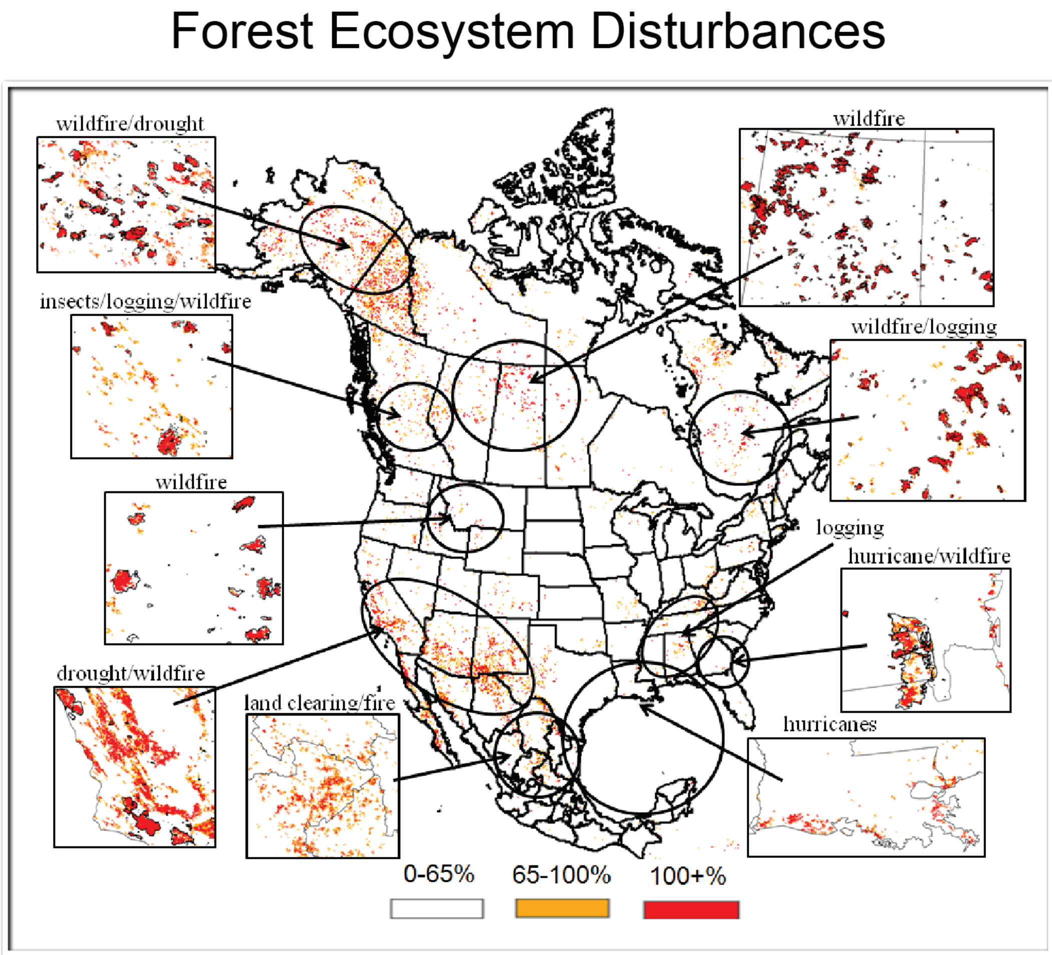

Figure 7.1: Forest Ecosystem Disturbances

Caption: The distribution of major forested ecosystem disturbance types in North America varies by topography, vegetation, weather patterns, climate gradients, and proximity to human settlement. Severity is mapped using the MODIS Global Disturbance Index, with moderate (orange) and high (red) severity. Fire along with other disturbances dominates much of the western forested ecosystems. Storms affect the Gulf Coast of the U.S., insect damage is widespread but currently concentrated in western regions, and timber harvest prevails in the Southeast. Figure source: (Goetz et al. 2012); Copyright 2012 American Geophysical Union.

Increasing Forest Disturbances

Climate change is increasing the vulnerability of forests to ecosystem change and tree mortality through fire, insect infestations, drought, and disease outbreaks. Western U.S. forests are particularly vulnerable to increased wildfire and insect outbreaks; eastern forests have smaller disturbances but could be more sensitive to periodic drought.

Insect outbreaks and pathogens, invasive species, wildfires, and extreme events such as droughts, high winds, ice storms, hurricanes, and landslides induced by storms (Dale et al. 2001) are all disturbances that affect U.S. forests and their management. These disturbances are part of forest dynamics, are often interrelated, and can be amplified by underlying trends – for example, decades of rising average temperatures can increase damage to forests when a drought occurs (Jentsch et al. 2007). Forest disturbances with large ecosystem effects occur relatively infrequently, making detection of changes related to climatic extremes more difficult than for changes in average conditions (CCSP 2009a; IPCC 2012; Smith 2011).

Factors affecting tree death, such as drought, higher temperatures, and/or pests and pathogens, are often interrelated, which means that isolating a single cause of mortality is rare (Allen et al. 2010; Dukes et al. 2009; McDowell et al. 2008). However, rates of tree mortality due to one or more of these factors have increased with higher temperatures in western forests (Van Mantgem et al. 2009; Williams et al. 2010) and are well correlated with both rising temperatures and associated increases in evaporative water demand (Williams et al. 2012). These factors are consistent with recent large-scale die-off events for multiple tree species observed across the United States (Allen et al. 2010; Raffa et al. 2008). In eastern forests, forest composition, forest structure, and pollutants appear to be more important than climate in causing large-scale tree mortality over recent decades. Nonetheless, tree mortality is sensitive to rising temperature (Dietze and Moorcroft 2011), and is expected to increase as climate warms. Because disturbances are normal yet rare at large scales, the extent to which recent forest disturbances can be directly attributed to climate change is uncertain. However, a growing body of research documents clear linkages between climatic conditions projected for the future and subsequent ecosystem responses, and confirms emerging risks to forests.

Future disturbance rates in forests will depend on changes in the frequency of extreme events as well as the projected underlying trends (Jentsch et al. 2007; Smith 2011). While past forest dynamics have been driven predominantly by drought only, future dynamics will be responding to drought and higher temperatures. Trees die faster when higher temperatures accompany drought; thus a shorter drought can trigger mortality. Short droughts occur more frequently than long droughts, therefore the direct effect of rising temperatures, without a change in drought frequency, could result in substantially greater mortality (Adams et al. 2009). Further, this type of disturbance will be compounded by other interacting factors, such as more frequent and/or severe drought, biotic disturbances, and land-use change.

Given strong relationships between climate and fire, even when modified by land use and management, projected climate changes suggest that western forests in the United States will be increasingly affected by large and intense fires that occur more frequently (Bowman et al. 2009; Keane et al. 2009; Littell et al. 2009; Westerling et al. 2011; Williams et al. 2010). Eastern forests are less likely to experience immediate increases in wildfire, unless a point is reached at which rising temperatures combine with seasonal dry periods, more protracted drought, and/or insect outbreaks to trigger wildfires, such as has been seen in Florida (see Ch.17: Southeast).

Extensive tree mortality or decline in growth rates are projected to increase under future climate conditions for western forests and eastern forests, in response to drought, rising temperatures, and/or pests and pathogens (Adams et al. 2009; Allen et al. 2010; Bentz et al. 2010). Although rising temperatures and CO_2 levels can increase growth or migration of tree species (Saxe et al. 2008; Vose et al. 2012; Woodall et al. 2009), most eastern species groups exhibit increases in mortality with rising temperature (Dietze and Moorcroft 2011). Tree mortality is often a combination of many factors, thus increases in pollutants, droughts, and wildfires will increase the probability of a tree dying. Under projected climate conditions, rising temperatures could become more important than, or work together with, stand characteristics and these other stressors to increase mortality. As temperatures increase to levels projected for mid-century and beyond, eastern forests may be at risk of die-off or decline (Dale et al. 2010b) similar to recent die-offs in western forests (Allen et al. 2010; Raffa et al. 2008), which already have been more severe even than recent estimates (IPCC 2007). New evidence indicates that most tree species maintain only a small hydraulic safety margin, reinforcing the idea that mesic as well as semiarid forests are vulnerable to drought-induced mortality under warming climates (Choat et al. 2012).

Consequences of large scale die-off and wildfire disturbance events pose major challenges to forest management, as impacts cut across all major categories of ecosystem goods and services. These events could have potential impacts occurring at up to regional scales for timber, flooding and erosion risks, other changes in water budgets, biogeochemical changes including carbon storage, and aesthetics (Adams et al. 2010; Allen et al. 2010; Anderegg et al. 2012; Breshears et al. 2011; Campbell et al. 2009; Ehrenfeld 2010; Hicke et al. 2012). Rising disturbance rates can increase harvested wood output and potentially lower prices, particularly given that annual U.S. forest growth currently exceeds harvesting. However, higher disturbance rates will make forest investments more risky and more costly; thus output are likely to be lowered. Western forests could also lose substantial amounts of carbon storage capacity as a result of high disturbance events. For example, high disturbance events such as increased wildfires, insect outbreaks and droughts that are severe enough to alter soil moisture and nutrients can result in changes in tree density or species composition (Hicke et al. 2012). This would result in considerable carbon losses, and as a consequence, alter long-term carbon storage or the rate of carbon cycling (Hicke et al. 2012). In addition, projections to date of potential increases in carbon storage may not adequately estimate die-off and wildfire conditions under higher temperatures (McDowell et al. 2011; North et al. 2009).

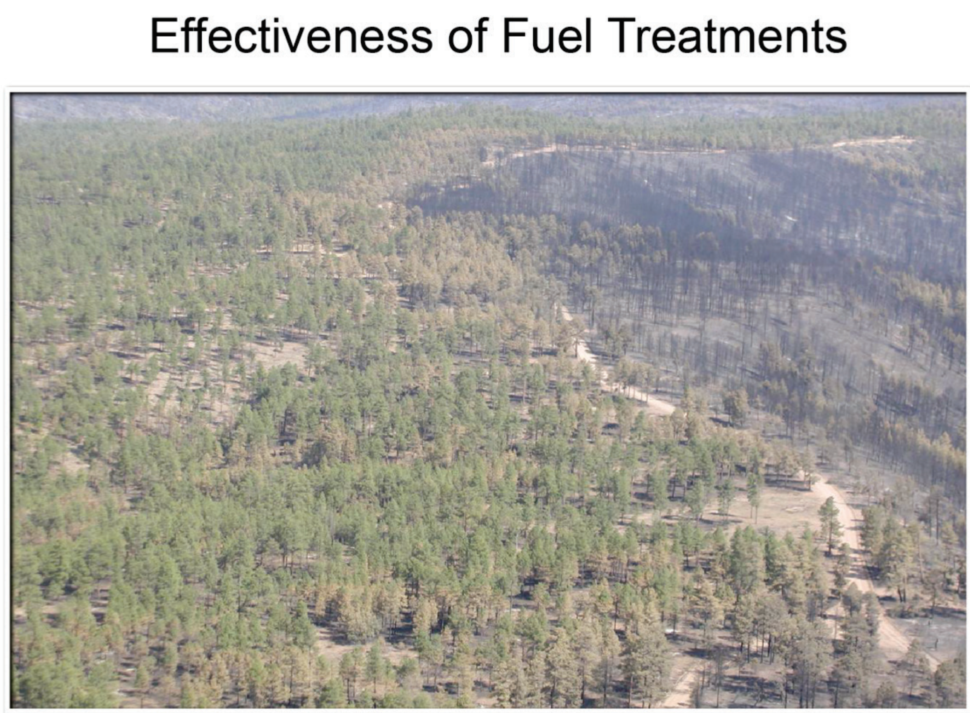

Figure 7.2: Effectiveness of Fuel Treatments

Caption: Forest treatments that maintain uneven-aged forest structure and create small openings in the forest can help prevent large wildfires from spreading. Photo shows the effectiveness of fuel treatments in Arizona's 2002 Rodeo-Chediski fire, which burned more than 400 square miles, at the time the worst fire in state history. Unburned area (left) had been managed with a treatment that removed commercial timber, thinned non-commercial sized trees, and followed a prescribed fire in 1999, while the upper right side of the photo shows burned area in untreated slope below Limestone Ridge. (Photo credit Jim Youtz, U.S. Forest Service)

Changing Carbon Uptake

U.S. forests currently absorb about 13% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake.

Climate-related Effects on Trees and Forest Productivity

Forests within the U.S. grow across a wide range of latitudes and altitudes and occupy all but the driest regions. Current forest cover has been mostly shaped by topography, disturbance frequency, and human activity. Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth was limited by low temperatures and short growing seasons, but are gradually being altered by climate change (Boisvenue and Running 2006; Caspersen et al. 2000; Joos et al. 2002; McKenzie et al. 2001). However, these trends are not universal. Under some observed and projected case studies, while growing season lengthened, the number of days with snow on the ground decreased and water stress increased, as it did in the Rocky Mountain forests (Boisvenue and Running 2010). In the eastern U.S., elevated CO_2 and temperature may increase forest growth and potentially carbon storage, if sufficient water is available. Ecological models project that much of the U.S. will experience species shifts in forests and other vegetation types, suggesting major changes in species composition on more than 5% to 20% of the land area in the U.S. by 2100 (Ch. 8: Ecosystems).

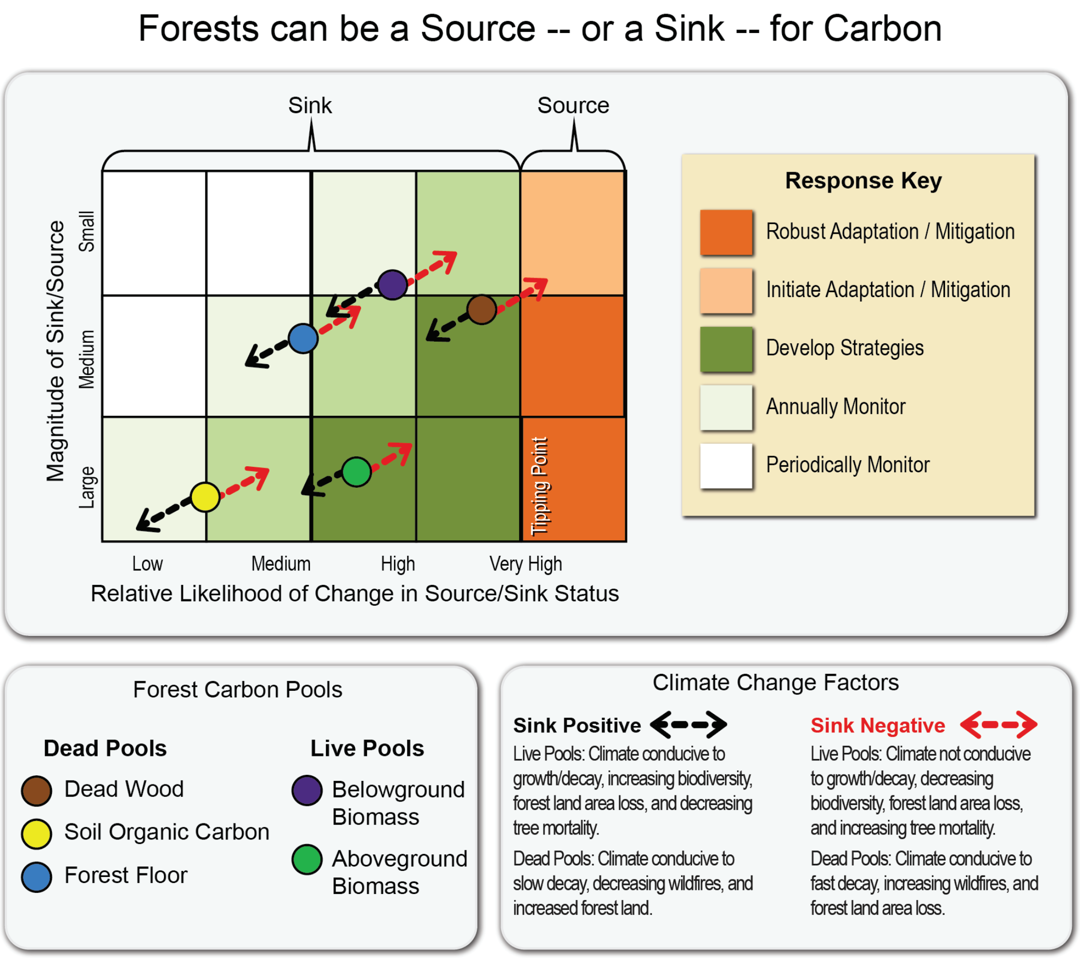

Figure 7.3: Forests can be a Source – or a Sink – for Carbon

Caption: Chart shows risk analysis of forest carbon processes as related to availability of current and future soil moisture. Western forests are currently considered limited by moisture and thereby highly susceptible to future changes in environmental conditions. The beneficial effects of elevated CO_2 and the extended growing season length in moderately moist eastern forests will allow opportunity for carbon gain, even though water stress in summer months may increase if precipitation decreases. In contrast, dry eastern forests, though adapted to periodic moisture deficits, will see loss of carbon. Source: (Vose et al. 2012).

Forest Carbon Sequestration and Carbon Management

From the onset of European settlement to the start of the 20th century, changes in U.S. forest cover due to expansion of agriculture, tree harvests, and settlements resulted in net emissions of carbon (Birdsey et al. 2006; McKinley et al. 2011). More recently, with cropland abandonment to forests, technological advances in harvesting, and changes in forest management, U.S. forests now serve as a substantial carbon sink, capturing and storing more than 270 million tons of carbon per year (EPA 2012; King et al. 2007). The amount of carbon taken up by U.S. land sinks is dominated by forests which have annually absorbed 7% to 24% (with a best estimate of about 13%) of fossil fuel CO_2 emissions in the U.S. over the past two decades. (See also the "Carbon Sink" box in Ch. 15: Biogeochemical Cycles.)

The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (see above), as well as shifts in tree species, ranges, and productivity (Dale et al. 2010b; McKinley et al. 2011). Economic factors will affect the future carbon cycle of forests, as the age class and condition of forests are affected by the acceleration of harvesting (EPA 2005; Goodale et al. 2002), land-use changes such as urbanization (USFS 2012), changes in forest types (Sohngen and Brown 2006), and bioenergy development (Choi et al. 2011; Daigneault et al. 2012; DOE 2011; USFS 2012). Societal choices about forest policy will also affect the carbon cycles on public and private forestland.

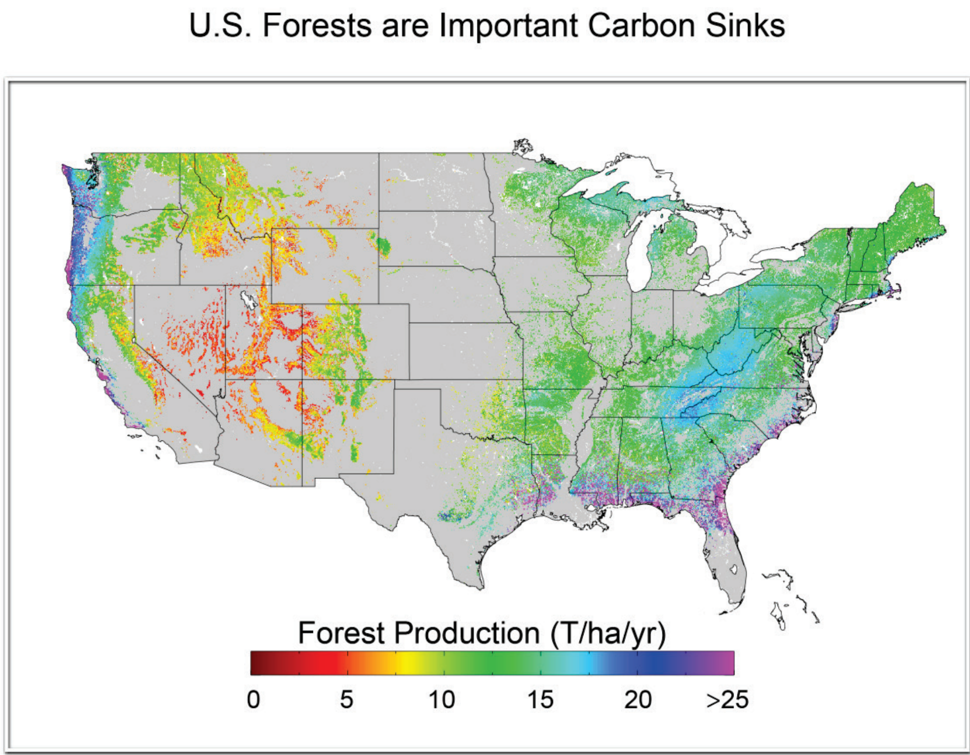

Figure 7.4: U.S. Forests are Important Carbon Sinks

Caption: U.S. Forests currently absorb about 13% of national carbon dioxide emissions. Southwest forests absorb considerably less than many eastern forests and those along the western coast. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake. Figure shows carbon uptake rates for U.S. forests in tons per hectare per year (methods from Running et al. 2004).

Efforts to reduce atmospheric CO_2 levels through forest management and forest product use focuses on three strategies: 1) land-use change to increase forest area (afforestation) and/or to avoid deforestation; 2) carbon management in existing forests; and 3) use of wood as a tool to reduce future climate change (for example, using wood to replace materials such as steel and concrete that require more carbon emissions to produce, to replace fossil fuels for energy production; or in wood products for carbon storage).

In the U.S., afforestation (active establishment or planting of forests) could capture and store a maximum of 225 million tons of carbon per year from 2010−2110 (EPA 2005; King et al. 2007). Tree and shrub encroachment into grasslands, rangelands, and savannas provides a large potential carbon sink that could exceed half of what existing U.S. forests capture and store annually (King et al. 2007).

Expansion of urban and suburban areas is responsible for much of the current and expected loss of U.S. forests (USFS 2012). In addition, the increasing prevalence of extreme conditions that encourage wildfires can convert some forests to shrublands and meadows (Westerling et al. 2011), or permanently reduce carbon stocks on existing forests if fires occur more frequently (Balshi et al. 2009; Harden et al. 2000).

Carbon management on existing forests can include practices that increase forest growth, such as fertilization, irrigation, switching to fast-growing planting stock, shorter rotations, and weed, disease, and insect control (Albaugh et al. 2003; Albaugh et al. 2004; Allen 2008; Amishev and Fox 2006; Borders et al. 2004; Nilsson and Allen 2003). In addition, forest management can increase average forest carbon stocks by increasing the interval between harvests or decreasing harvest intensity (Balboa-Murias et al. 2006; Harmon and Marks 2002; Harmon et al. 2009; Jiang et al. 2002; Kaipainen et al. 2004; Seely et al. 2002). Since 1990, CO_2 emissions from wildland forest fires in the lower 48 United States have averaged about 67 million tons of carbon per year (EPA 2009, 2010). While fuel treatments reduce on-site carbon stocks, they can contribute to reducing future climate change by providing a feedstock for bioenergy, and by possibly avoiding future, potentially larger, wildfire emissions (Vose et al. 2012).

Increased use of wood products in construction, particularly for nonresidential buildings, can reduce the use of materials that emit more CO_2 in their manufacture, and thus substantially offset CO_2 emissions (McKinley et al. 2011). The carbon emissions offset from using wood rather than alternate materials for a range of applications can be two or more times the carbon content of the product (Sathre and O'Connor 2010).

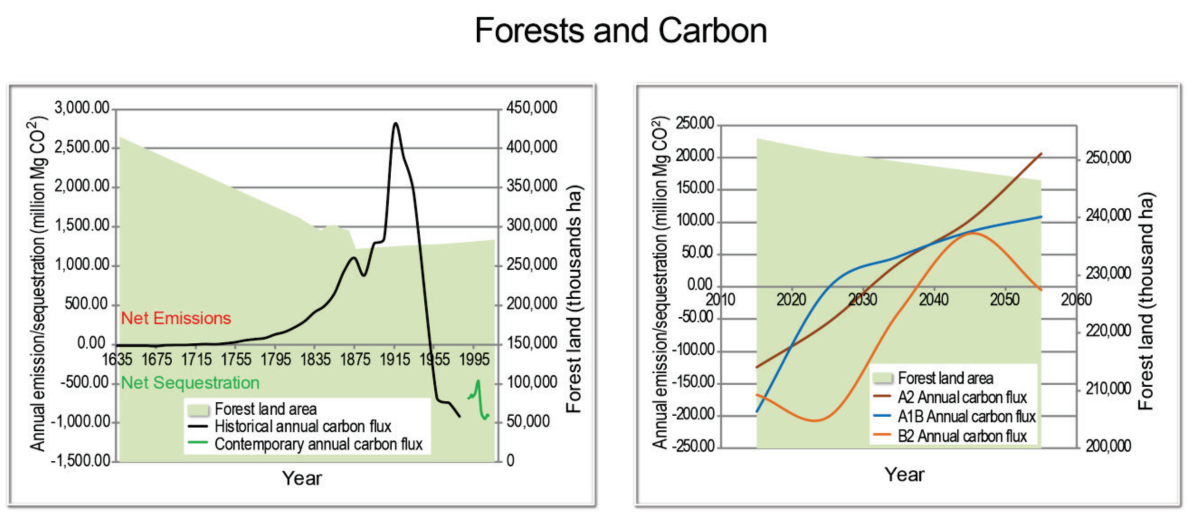

Figure 7.5: Forests and Carbon

Caption: Historic, contemporary, and future projections of annual rates of forest ecosystem and harvested wood product CO_2 net emissions/sequestration in U.S. forests, from 1635 to 2055. In the left panel, the change in the historical annual carbon emissions (black line) in the early 1900s corresponds to the peak in the transformation of large parts of the U.S. from forested land to agricultural land uses. In the right panel, future projections are shown under high (A2) and lower (B2 and A1B) emissions scenarios. (From EPA 2012; USFS 2012).

Bioenergy Potential

Bioenergy is an emerging new market for wood; with higher wood prices, development of a market in salvaged wood from trees killed by drought, insects, and fire could help finance salvage and restoration activities and reduce U.S. fossil fuel consumption. However, the environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.

Bioenergy refers to the use of plant-based material to produce energy, and comprises about 28% of the U.S. renewable energy supply (Ch. 10, Water, Energy, Land). The *maximum* projected potential for forest bioenergy ranges from between 3% and 5% of total current U.S. energy consumption (Smith et al. 2012). Bioenergy from all sources, both agricultural and forest resources, could theoretically replace up to 30% equivalent of U.S. petroleum consumption, but only if all relevant policies were optimized (DOE 2011). Forest biomass energy could be one component of an overall bioenergy strategy to reduce emissions of carbon from fossil fuels (Perlack et al. 2005; Zerbe 2006), while also improving water quality (Dale et al. 2010a; Robertson et al. 2008) and maintaining lands for timber production in the face of other pressures (DOE 2011). Active biomass energy markets using wood and forest residues have emerged in the South and Northeast, particularly in states that have adopted renewable fuel standards.

The economic viability of using forest product for bioenergy depends on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution, and use (Efroymson et al. In press; NRC 2011). Socioeconomic effects include social well-being, energy security, trade, profitability, resource conservation, and social acceptability (Dale et al. in press).

The potential for biomass energy to increase timber harvests has led to debates about whether forest biomass energy leads to higher carbon emissions. (Bright et al. in press; Daigneault et al. 2012; Hudiburg et al. 2011; Schulze et al. 2012; Zanchi et al. 2011). The debate revolves around model assumptions in policy analyses, temporal horizons defined, and the life cycle domain defined. The change in carbon balance over time may differ, depending on forest management scenarios. For example, utilizing natural beetle-killed forests will yield a different carbon balance than growing and harvesting a live, fast-growing plantation.

Markets for energy from biomass appear to be ready to grow in response to energy pricing, policy, and demand (Daigneault et al. 2012), although recent increases in the supply of natural gas have reduced the perceived urgency for new biomass projects. Further, because energy facilities typically buy the lowest-quality wood at prices that rarely pay much more than cutting and hauling costs, they often require a viable saw timber market nearby to ensure an adequate, low-cost supply of material (Galik et al. 2009). As bioenergy markets require a stable resource for efficient mill/plant supply, disturbances may introduce opportunities for enhanced supply through salvage efforts. These disturbances, while providing biomass for energy production, may be potentially disruptive to the mill supply chain for traditional wood products. While this bioenergy market allows managers to eliminate wastes and conduct forest health, stand improvement, and climate adaptation operations, it has yet to be made a profitable enterprise in most U.S. regions.

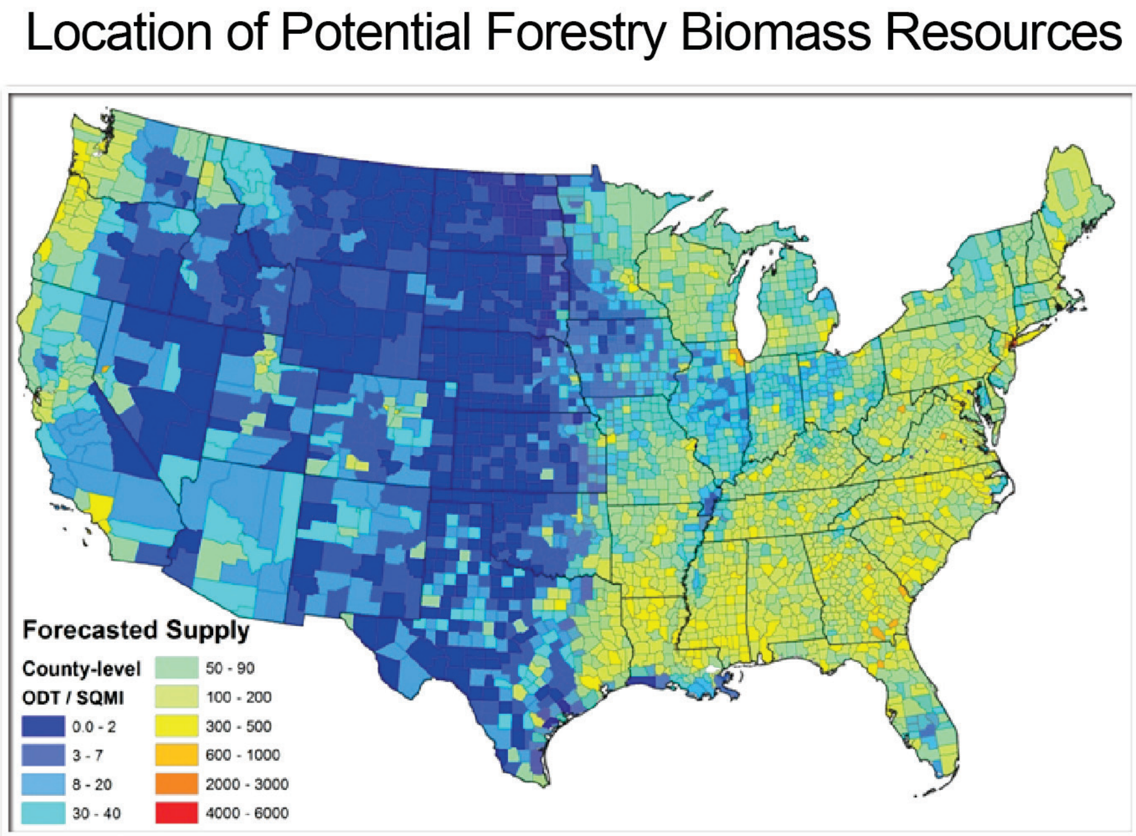

Figure 7.6: Location of Potential Forestry Biomass Resources

Caption: Potential forestry bioenergy resources by 2030 at $80 per dry ton of biomass based on current forest area, production rates based on aggressive management for fast-growth, and short rotation bioenergy plantations. Units are Oven Dry Tons (ODT) per Square Mile at the county level, where an ODT is 2,000 pounds of biomass from which the moisture has been removed. Includes extensive material from existing forestland such as residues, simulated thinnings, and some pulpwood for bioenergy, among other sources. Source: based on (DOE 2011).

Influences on Management Choices

The changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy will all influence forest management responses to climate change. However, development of and better access to practical and timely information for managers to consider in choosing adaptation and mitigation options will facilitate management of public and private forestland.

Owner objectives, markets for wood products, monetary value of private land, and policies governing private and federal forest land influence the actions taken to manage U.S. forestlands (56% private, 44% public). Less than 1% of the volume of commercial trees from U.S. forestlands is harvested annually, and 92% of this harvest comes from private forestlands (Smith 2009). Among corporate owners (18% of all forestland), ownership has shifted from forest industry to investment management organizations that may or may not have active forest management as a primary objective. Non-corporate private owners, an aging demographic, manage 38% of forestland. Primary objectives for many of these private landowners are maintaining aesthetics, sustaining the privacy that the land provides, and retaining its importance as part of their family legacy (Butler 2008). Many family forest owners feel it is necessary to keep the woods healthy but many are not familiar with forest management practices (Butler 2008).

The market for timber will continue to be driven by development (or lack of development) in large scale forest-product enterprises that serve increasingly competitive global markets (Ince 2007). The emerging market for bioenergy is not yet profitable in most parts of the U.S. A significant economic factor facing private forest owners is the value of their forestlands for conversion to urban or developed uses. Urban conversions of forestland in the Midwest, Northeast, and South regions could result in the loss of 29.5 to 35.9 million acres (Plantinga et al. 2011). The willingness of private forest owners to actively manage forests in the face of climate change will be affected primarily by market and policy incentives, not climate change itself.

Forty-four percent of U.S. forestland (329 million acres) is controlled by public agencies: federal (33%); state (9%); and county and municipal government (1%) (Smith et al. 2009). These lands serve many objectives such as wildlife habitat, watershed protection for urban drinking water, recreation, and timber harvest. Incentives for active forest management are influenced by societal values on public land management and, just as on private land, by the wood products market.

The ability of forest owners and forest managers to adapt to, and/or reduce, future climate change is enhanced by their capacity to alter management regimes relatively rapidly in the face of changing conditions. Private forest owners have been highly responsive to market and policy signals, especially in the southeastern U.S. (Wear and Prestemon 2004). Thus, private landowners may be able to capitalize on existing options for forest management to reduce disturbance effects, increase the capture and storage of carbon, and promote adaptation of new species under climate change. Management practices that can be used to reduce disturbance effects include: altering tree planting and harvest strategies through species selection and timing; factoring in genetic variation; managing for reduced stand densities, which could reduce wildfire risk (particularly at rural-urban interfaces); reducing other stressors such as poor air quality; using forest management practices to minimize drought stress; and developing regional networks to aid in impacts on ecosystem goods and services (Breshears et al. 2011; Joyce et al. 2008; Millar et al. 2007; Vose et al. 2012). Legally binding regulatory requirements may penalize adaptive or innovative management in the face of climate change, as regulators may force actions that are required, but inconsistent with changing or future conditions. These regulations presume a static environment where plants, animals, and ecosystems are not responding to climate change (Millar and Swanston 2012).

Lack of fine-scale information on the possible effects of climate changes on locally managed forests limits the ability of managers to weigh these risks to their forests against the economic risks of implementing forest management practices such as adaptation and/or mitigation treatments. This knowledge gap will impede the implementation of effective management on public or private forestland in the face of climate change.

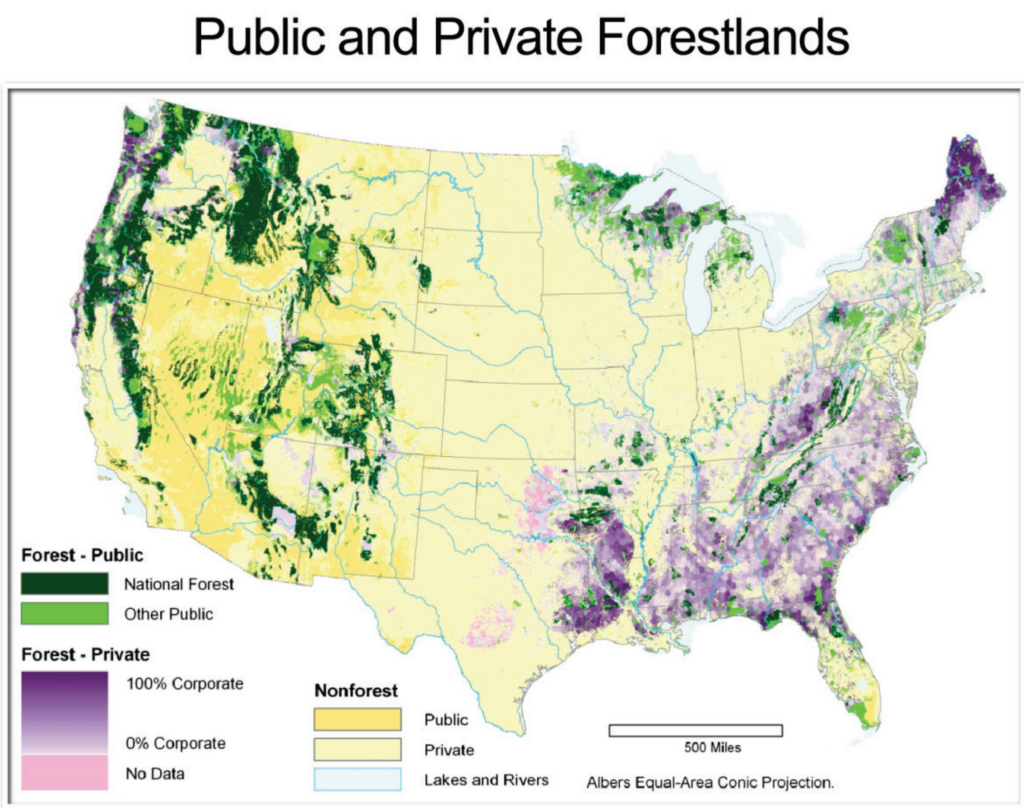

Figure 7.7: Public and Private Forestlands

Caption: Forest land by ownership category in the contiguous U.S., 2007 (USFS 2012). Western forests are most often located on public lands, while eastern forests, especially in Maine and in the Southeast, are more often privately held.

Traceable Accounts

Chapter 7: Forestry

Key Message Process: A central component of the process was a workshop held in July 2011 by the USDA Forest Service to guide the development of the technical input report. This session, along with numerous technical teleconferences, led to the foundational technical input report, the National Climate Assessment—Forest Sector Technical Report. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station (Vose et al. 2012).

The chapter authors engaged in multiple technical discussions via teleconference between January and June 2012, which included careful review of the foundational and of 55 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the lead author of each message.

Key message	**Climate change is increasing the vulnerability of forests to fire, insect infestations, drought, and disease outbreaks. Western U.S. forests are particularly vulnerable to increased wildfire and insect outbreaks; eastern forests have smaller disturbances but are projected to be more sensitive to periodic drought.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Dale et al. 2001 addressed a number of factors that will affect U.S. forests and how they are managed. This is supported by additional publications focused on effects of drought and by more large scale tree die-off events (Adams et al. 2009; Allen et al. 2010; Bentz et al. 2010), wildfire (Bowman et al. 2009; Keane et al. 2009; Littell et al. 2009; Westerling et al. 2011; Williams et al. 2010), insects and pathogens (Adams et al. 2009; Allen et al. 2010; Bentz et al. 2010). Other studies support the negative impact of climate change by examining the tree mortality rate due to rising temperatures (Adams et al. 2009; Allen et al. 2010; Dale et al. 2010b; Jentsch et al. 2007; Raffa et al. 2008; Van Mantgem et al. 2009; Williams et al. 2010; Williams et al. 2012) which is projected to increase in some regions (Adams, 2009). Although it is difficult to detect a trend in disturbances because they are inherently infrequent and it is impossible to attribute an individual disturbance event to changing climate, there is nonetheless much that past events, including recent ones, reveal about expected forest changes to future climate. Correlations with climate that include extreme events and/or modifications in atmospheric demand related to warmer temperature show strong associations with forest disturbance in observational (Williams et al. 2012) and experimental (Adams et al. 2009) studies. Figure 1. This figure uses a figure from (Goetz et al. 2012) which uses the MODIS Global Disturbance Index (MGDI) results from 2005 to 2009 to illustrate the geographic distribution of major ecosystem disturbance types across North America (based on (Mildrexler et al. 2009; Mildrexler et al. 2007)). The MGDI uses remotely sensed information to assess the intensity of the disturbance. Following the occurrence of a major disturbance, there will be a reduction in Enhanced Vegetation Index (EVI) because of vegetation damage; in contrast, Land Surface Temperature (LST) will increase because more absorbed solar radiation will be converted into sensible heat as a result of the reduction in evapotranspiration from less vegetation density. MGDI takes advantage of the contrast changes in EVI and LST following

	disturbance to enhance the signal to effectively detect the location and intensity of disturbances (http://www.ntsg.umt.edu/project/mgdi). Moderate severity disturbance is mapped in orange and represents a 65–100% divergence of the current year MODIS Global Disturbance Index value from the range of natural variability, High severity disturbance (in red) signals a divergence of over 100%. (from Goetz et al. 2012).
New information and remaining uncertainties	Forest disturbances have large ecosystem effects, but high interannual variability in regional fire and insect activity makes detection of trends more difficult than for changes in mean conditions (CCSP 2009a; IPCC 2012; Smith 2011). Therefore, there is generally less confidence in assessment of future projections in disturbance events than for mean conditions (for example, growth under slightly warmer conditions) (IPCC 2012). There are insufficient data on trends in windthrow, ice storms, hurricanes, and landslide-inducing storms to infer that these types of disturbance events are changing. Factors affecting tree death, such as drought, warmer temperatures, and/or pests and pathogens are often interrelated, which means that isolating a single cause of mortality is rare (Adams et al. 2009; Allen et al. 2010; Dukes et al. 2009; McDowell et al. 2008; McDowell et al. 2011; Williams et al. 2012).
Assessment of confidence based on evidence	**Very High**. There is very high confidence that under projected climate changes there is high risk (high risk = high probability and high consequence) that western forests in the United States will be impacted increasingly by large and intense fires that occur more frequently (Bowman et al. 2009; Keane et al. 2009; Littell et al. 2009; Westerling et al. 2011; Williams et al. 2010). This is based on the strong relationships between climate and forest response, shown observationally (Williams et al. 2012) and experimentally (Adams et al. 2009). Expected responses will increase substantially to warming, to warming in combination with drought, and also in conjunction with other changes such as an increase in the frequency and/or severity of drought and amplification of pest and pathogen impacts. Eastern forests are less likely to experience immediate increases in wildfire unless/until a point is reached at which warmer temperatures, concurrent with seasonal dry periods or more protracted drought, trigger wildfires.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See Key Message #1.

Key message #2/4	**U.S. forests currently absorb 13 percent of all carbon dioxide (CO_2) emitted in the U.S. Climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. A recent study (EPA 2012) has shown that the forests are a big sink of CO_2 nationally. However, permanence of this carbon sink is contingent on changing forest disturbance rates and economic conditions that may accelerate harvest of forest biomass.(Dale et al. 2010a). Market response can cause shifts in forest age (EPA 2005; Goodale et al. 2002), land-use changes and urbanization reduce/limit forested areas (USFS 2012), forest type changes shift the dynamics of the area (Sohngen and Brown 2006), and bioenergy development can change how we manage forests (Choi et al. 2011; Daigneault et al. 2012; DOE 2011; USFS 2012). Additionally, publications have reported that fires can convert a forest into a shrubland or meadow (Westerling et al. 2011), with frequent fires permanently reducing the carbon stock (Balshi et al. 2009; Harden et al. 2000).
New information and remaining uncertainties	That economic factors and societal choices will affect future carbon cycle of forests is known with certainty; the major uncertainties come from the future economic picture, accelerating disturbance rates, and how societal responses to those dynamics.
Assessment of confidence based on evidence	Based on the evidence and uncertainties, confidence is **high** that, in the U.S., climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake**.** The U.S. has already seen large-scale shifts in forest cover from interactions between forest land use and agriculture (for example, onset of European settlement to the present). Demands for forest land use exist today. The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (key message 1) growth rates, and harvest demands.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See Key Message #1.

Key message #3/4	**Bioenergy is an emerging new market for wood; with higher wood prices, development of a market in salvaged wood from trees killed by drought, insects, and fire could help finance salvage and restoration activities and reduce U.S. fossil fuel consumption. However, the environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.**
Description of evidence base	The key message and supporting text summarize extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Studies have shown that harvesting forest bioenergy can prevent carbon emissions (Perlack et al. 2005; Zerbe 2006) and replace a portion of U.S. energy consumption to help reduce future climate change. Some newer literature has explored how use of forest bioenergy can replace a portion of current U.S. energy production from oil (DOE 2011; Smith 2011). Some more recent publications have reported some environmental benefits, such as improved water quality (Dale et al. 2010a; Robertson et al. 2008) and better management of timber lands (US DOE, 2011), and numerous socioeconomic benefits (Dale et al. in press) that can result from forest bioenergy implementation.
New information and remaining uncertainties	The implications of forest product use for bioenergy depend on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution and use (Efroymson et al. In press; NRC 2011). The potential for biomass energy to increase forest harvests has led to debates about whether biomass energy is net carbon neutral (Bright et al. in press; Hudiburg et al. 2011; Schulze et al. 2012; Zanchi et al. 2011). The debate revolves around model assumptions in energy conversion analyses, temporal horizons and the life cycle domain defined. The market for energy from biomass appears to be ready to grow in response to energy pricing, policy and demand; however, this industry is yet to be made a large-scale profitable enterprise in most regions of the United States.
Assessment of confidence based on evidence	**High**. Forest growth substantially exceeds annual harvest for normal wood and paper products, and much forest harvest residue is now un-utilized. Forest bioenergy will become viable if policy and economic energy valuations make it competitive with fossil fuels.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See Key Message #1.

Key message #4/4	**The changing nature of private forestland ownership, globalization of forestry markets, emerging markets for energy, and U.S. climate change policy will all influence forest management responses to climate change. However, development of and better access to practical and timely information for managers to consider in choosing adaptation and mitigation options will facilitate management of public and private forestland.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Forestry Technical Input (Vose et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The forest management response to climate change has been studied from varying angles. Publications on the effects of private ownership have shown both negative (Plantinga et al. 2011) and positive aspects (Wear and Prestemon 2004). An earlier study explored the effects of globalization (Ince 2007) and a newer study looked at the effect of U.S. climate change policy (Millar and Swanston 2012). One of the biggest issues deals with the lack of information that results in inaction from many forest owners (Butler 2008).
New information and remaining uncertainties	Global and national economic events will have an integral impact, but it is uncertain to what magnitude.
Assessment of confidence based on evidence	**Medium**. Human concerns regarding the effects of climate change on forests and the role of adaptation and mitigation will be viewed from the perspective of the values that forests provide to human populations, including timber products and water, recreation, and aesthetic and spiritual benefits (Vose et al. 2012). Many people, organizations, institutions, and governments influence the management of U.S. forests. Economic opportunities influence the amount and nature of private forestland (and much is known quantitatively about this dynamic) and societal values have a strong influence on how public forestland is managed. However, it remains challenging to project exactly how humans will respond to climate change in terms of forest management.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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8. Ecosystems, Biodiversity, and Ecosystem Services

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Key Messages

1. **Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.**
2. **Climate change combined with other stressors is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.**
3. **Land- and sea-scapes are changing rapidly and species, including many iconic species, may disappear from regions where they have been prevalent, changing some regions so much that their mix of plant and animal life will become almost unrecognizable.**
4. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, will shift, leading to important impacts on species and habitats.**
5. **Ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society.**

Climate change affects the living world, including people, through changes in ecosystems, biodiversity, and ecosystem services. Ecosystems entail all the living things in a particular area as well as the non-living things with which they interact, such as air, soil, water, and sunlight (Chapin et al. 2011). Biodiversity refers to the variety of life, including the number of species, life forms, genetic types, and habitats and biomes (which are characteristic groupings of plant and animal species found in a particular climate). Biodiversity and ecosystems produce a rich array of benefits that people depend on, including fisheries, drinking water, fertile soils for growing crops, climate regulation, inspiration, and aesthetic and cultural values (Millenium Ecosystem Assessment 2005). These benefits are called "ecosystem services" – some of which, like food and fisheries, are more easily quantified than others, such as climate regulation or cultural values.

Ecosystem services translate into jobs, economic growth, health, and human well-being.

Although ecosystems and ecosystem services are what we interact with every day, their linkage to climate change can be elusive because they are influenced by so many additional entangled factors. Ecosystem perturbations driven by climate change have direct human impacts, including reduced water supply and quality, the loss of iconic species and landscapes, distorted rhythms of nature, and the potential for extreme events to overcome the regulating services of ecosystems. Even with these well-documented ecosystem impacts, it is often difficult to quantify human vulnerability that results from shifts in ecosystem processes and services. For example, although it is straightforward to predict how precipitation will change water flow, it is much harder to pinpoint which farms and cities will be at risk of running out of water, and even more difficult to say how people will be affected by the loss of a favorite fishing spot or a wildflower that no longer blooms in the spring. A better understanding of how everything from altered water flows to the loss of wildflowers matters to people may be key to managing ecosystems in a way that promotes resilience to climate change.

Water

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Ecosystems modify climate-driven factors that control water availability and quality. Land-based ecosystems regulate the water cycle and are the source of sediment and other materials that make their way to aquatic ecosystems (streams, rivers, lakes, estuaries, oceans). Aquatic ecosystems provide the critically important services of storing water, regulating water quality, supporting fisheries, providing recreation, and carrying water and materials downstream. Humans utilize, on average, the equivalent of more than 40% of renewable supplies of freshwater in more than 25% of all watersheds (USGS 2012). Freshwater withdrawals are even higher in the arid Southwest, where the equivalent of 76% of all renewable freshwater is appropriated by people (Sabo et al. 2010). In that region, climate change has decreased streamflow due to lower spring precipitation and reduced snowpack (Barnett et al. 2008; Ch. 3 Water Resources). Depriving ecosystems of water reduces their ability to provide high quality water to people and habitat for aquatic plants and animals.

Local extinctions of fish and other aquatic species are projected from the combined effects of increased water withdrawal and climate change (Spooner et al. 2011). In the U.S., 47% of trout habitat in the interior West would be lost by 2080 under a scenario (A1B) that assumes similar emissions to the A2 scenario used in this report through 2050 and a slow decline thereafter (Wenger et al. 2011).

Across the entire U.S., precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC). At high concentrations, nutrients that are required for life (such as nitrogen and phosphorus) can become pollutants and can promote excessive algae growth – a process known as eutrophication. Currently, many U.S. lakes and rivers are polluted (have concentrations above government standards) by excessive nitrogen, phosphorus, or sediment. There is a well-established link between nitrogen pollution and river discharge, and many studies show that recent increases in rainfall in several regions of the U.S. have led to higher amounts of nitrogen carried by rivers (Northeast: (Howarth et al. 2012; Howarth et al. 2006), California: (Sobota et al. 2009), Mississippi Basin: (Justic et al. 2005; McIsaac et al. 2002)). The Mississippi basin is yielding an additional 32 million acre-feet of water each year – equivalent to four Hudson Rivers – laden with materials washed from its farmlands. This flows into the Gulf of Mexico, which is the site of the nation's largest hypoxic (low oxygen) "dead" zone (USGS 2012). The majority of U.S. estuaries are moderately to highly eutrophic (Bricker et al. 2007).

Links between discharge and sediment transport are well established (Inman and Jenkins 1999), and cost estimates for in-stream and off-stream damages from soil erosion range from $2.1 to $10 billion per year (Clark 1985; Pimentel et al. 1995). These estimates include costs associated with damages to, or losses of, recreation, water storage, navigation, commercial fishing, and property damage, but do not include costs of biological impacts (Clark 1985). Commercially and recreationally important fish species such as salmon and trout that lay their eggs in the gravel at the edges of streams are especially sensitive to elevated sediment fluxes in rivers (Greig et al. 2005; Julien and Bergeron 2006; Newcombe and Jensen 1996; Scheurer et al. 2009; Scrivener and Brownlee 1989; Suttle et al. 2004). Sediment loading in lakes has been shown to have substantial detrimental effects on fish population sizes, community composition, and biodiversity (Donohue and Molinos 2009).

Dissolved organic carbon fluxes to rivers and lakes are strongly driven by precipitation (Pace and Cole 2002; Raymond and Saiers 2010; Zhang et al. 2010)*;* thus in many regions where precipitation is expected to increase, DOC loading will also increase. Dissolved organic carbon is the substance that gives many rivers and lakes a brown, tea-colored look. Precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use (Haaland et al. 2010), but also alter the ability of sunlight to act as nature's water treatment plant. For example, *Cryptosporidium*, a pathogen potentially lethal to the elderly, babies, and people with compromised immune systems, is present in 17% of drinking water supplies sampled in the U.S. (Rose et al. 1991). This pathogen is inactivated by doses of ultraviolet (UV) light equivalent to less than a day of sun exposure (Connelly et al. 2007; King et al. 2008). Similarly, UV exposures reduce fungal parasites that infect *Daphnia*, a keystone aquatic grazer and food source for fish (Overholt et al. 2012). Increasing DOC concentrations may thus reduce the ability of sunlight to regulate these UV-sensitive parasites.

Few studies have projected the impacts of future climate change on nitrogen, phosphorus, sediment, or DOC transport from the land to rivers. Given the tight link between river discharge and all of these potential pollutants, areas of the U.S. that are projected to see increases in precipitation, like the Northeast, Midwest, and mountainous West (Roy et al. 2012), will also see increases in excess nutrients, DOC, and sediments transported to rivers. One of the few future projections available suggests that downstream and coastal impacts of increased nitrogen inputs could be profound for the Mississippi Basin. Under a scenario in which CO_2 reaches double pre-industrial levels, a 20% increase in river discharge is expected to lead to higher nitrogen loads and a 50% increase in algae growth in the Gulf of Mexico, a 30% to 60% decrease in deep-water dissolved oxygen concentration, and an expansion of the dead zone (Justic et al. 1996). A recent comprehensive assessment (Howarth et al. 2012) shows that, while climate is an important driver, nitrogen carried by rivers to the oceans is most strongly driven by fertilizer inputs to the land. Therefore, in the highly productive agricultural systems of the Mississippi Basin, the ultimate impact of more precipitation on the expansion of the dead zone will depend on agricultural management practices in the basin (David et al. 2010; McIsaac et al. 2002; Raymond et al. 2012).

Rising air temperatures can also lead to declines in water quality through a different set of processes. Some large lakes, including the Great Lakes, are warming at rates faster than the world's oceans (Verburg and Hecky 2009) and the regions surrounding them (Schneider and Hook 2010). Warmer surface waters can stimulate blooms of harmful algae in both lakes and coastal oceans, which may include toxic cyanobacteria that are favored at higher temperatures (Paerl and Huisman 2008). Harmful algal blooms, which are caused by many factors, including climate change, exact a cost in freshwater degradation of approximately $2.2 billion annually (Dodds et al. 2009).

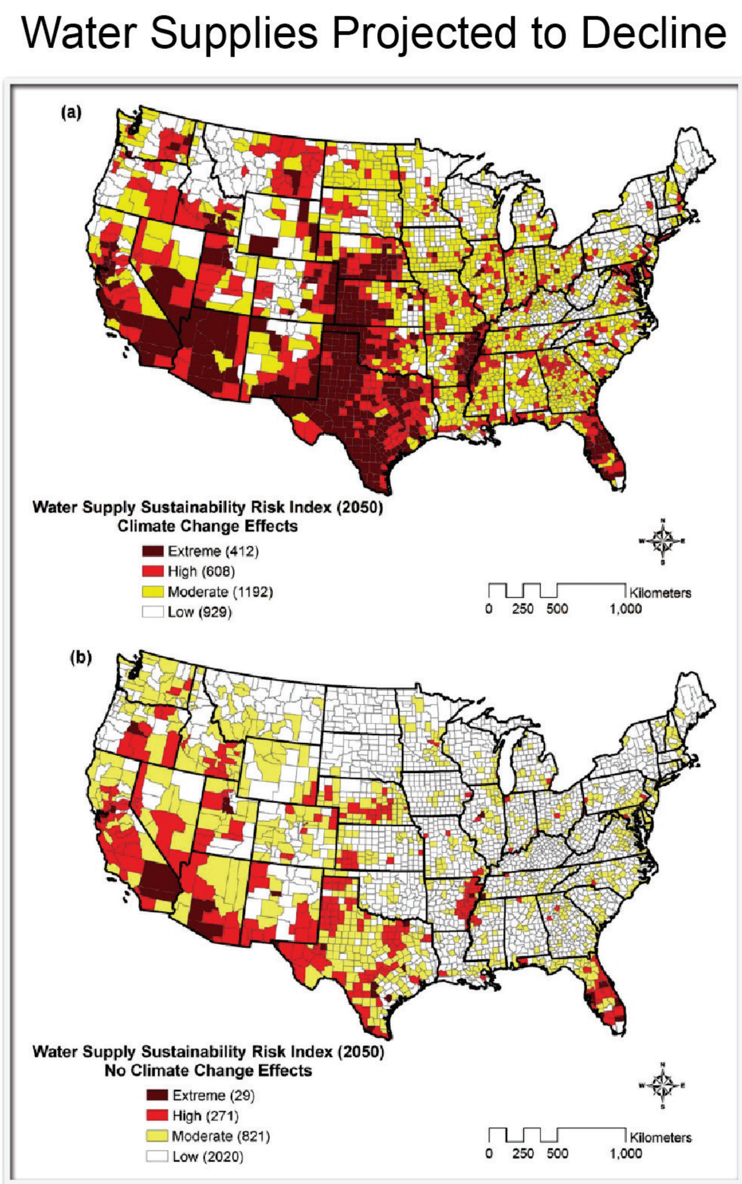

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Figure 8.1: Water Supplies Projected to Decline

Caption: Climate change is projected to reduce water availability in some parts of the country. Compared to 10% of counties today, by 2050, 32% of counties will be at risk of water shortages. Projections assume continued increases in emissions through 2050 and a slow decline thereafter (A1B scenario). (Source: Roy et al., 2012)

The Aftermath of Hurricanes

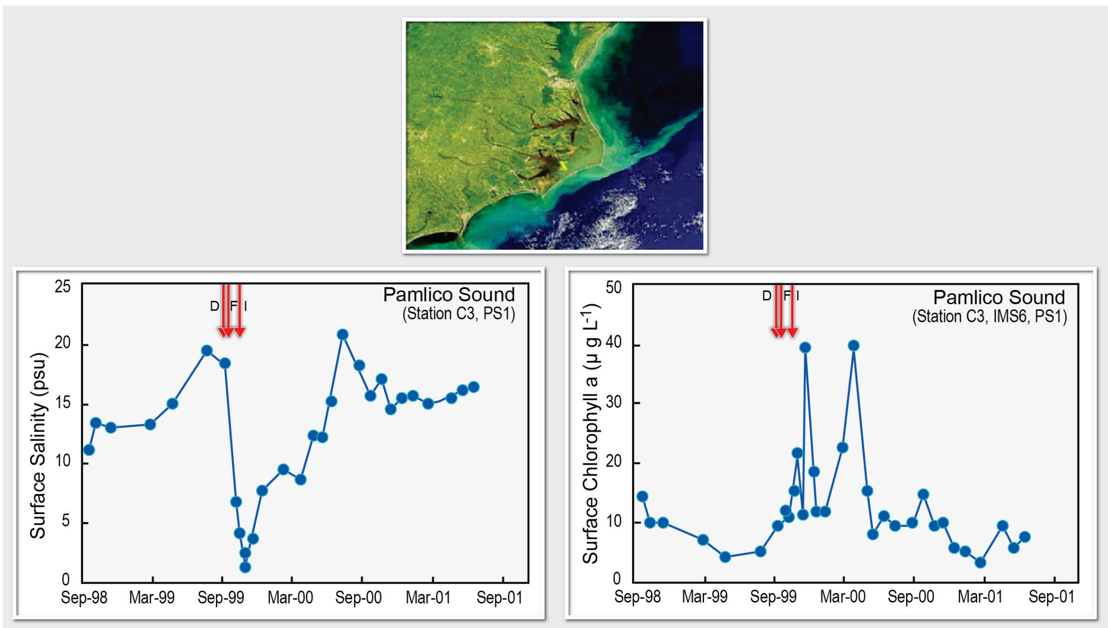

Figure 8.2: The Aftermath of Hurricanes

Caption: Hurricanes bring intense rainfall, which reduces the salinity of offshore water and leads to blooms of algae. Photo above shows Pamlico Sound, North Carolina, after Hurricane Floyd. Note light green area off the coast, which is new algae growth. The graph on the left shows a steep drop in salinity of ocean water due to the large influx of freshwater from rain after a series of hurricanes. Red arrows indicate Hurricanes Dennis, Floyd, and Irene, which hit sequentially during the 1999 hurricane season. The graph on the right shows a steep rise in the amount of surface chlorophyll after these hurricanes, largely due to increased algae growth. (Figure source: Paerl et al., 2003. Image source NASA SeaWiFS)

Extreme Events

Climate change combined with other stressors is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Ecosystems play an important role in "buffering" the effects of extreme climate conditions (floods, wildfires, tornados, hurricanes) on the movements of materials and flow of energy (Peters et al. 2011). Climate change and human modifications of ecosystems and landscapes often increase their vulnerability to damage from extreme events while at the same time reducing their natural capacity to modulate the impacts of such events. Salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against storm surges. Their losses – from coastal development, erosion, and sea level rise – render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (Ch. 25 Coastal Zone; FitzGerald et al. 2008; McGranahan et al. 2007). Floodplain wetlands, although greatly reduced from their historical extent, absorb floodwaters and reduce the impact of high flows on river-margin lands. Where they are lost to inundation, the consequences would be profound. In the Northeast, even a small sea level rise (1.6 feet) would dramatically increase the numbers of people (47% increase) and property loss (73% increase) impacted by storm surge in Long Island compared to present day storm surge impacts (Shepard et al. 2012). Extreme weather events that produce sudden increases in water flow and the materials it carries can decrease the natural capacity of ecosystems to process pollutants, both by reducing the amount of time water is in contact with reactive sites and by removing or harming the plants and microbes that remove the pollutants (FitzGerald et al. 2008; McGranahan et al. 2007).

Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 million (Hedde 2012).

Plants and Animals

Land- and sea-scapes are changing rapidly and species, including many iconic species, may disappear from regions where they have been prevalent, changing some regions so much that their mix of plant and animal life will become almost unrecognizable.

Vegetation model projections suggest that much of the U.S. will experience changes in the composition of species characteristic of an area. Studies applying different models for a range of future climates project biome changes for about 5 to 20% of the land area of the U.S. by 2100 (Alo and Wang 2008; Bergengren et al. 2011; Gonzalez et al. 2010; Sitch et al. 2008; USGS 2012). Many major changes, particularly in the western states and Alaska, will in part be driven by increases in fire frequency and severity. For example, the average time between fires in the Yellowstone National Park ecosystem is projected to decrease from 100 to 300 years to less than 30 years, potentially resulting in a shift from coniferous (pine, spruce, etc.) forests to woodlands and grasslands (Westerling et al. 2011). Warming has also led to novel wildfire occurrence in ecosystems where it has been absent in recent history, such as arctic Alaska and the southwestern deserts. Extreme weather conditions linked to sea ice decline in 2007 led to the ignition of the Anaktuvuk River Fire, which burned more than 380 square miles of arctic tundra that had not been disturbed by fire for over 3,000 years (Hu et al. 2010). This one fire (which burned deeply into organic peat soils) released enough carbon to the atmosphere to offset all of the carbon taken up by the entire arctic tundra biome over the past quarter-century (Mack et al. 2011).

In addition to shifts in species assemblages, there will also be changes in species distributions (Chen et al. 2011). In recent decades in land and aquatic environments, plants and animals have moved to higher elevations at a median rate of 36 feet (0.011 kilometers) per decade, and to higher latitudes at a median rate of 10.5 miles (16.9 kilometers) per decade. As climates continue to change, models and long-term studies project even greater shifts in species ranges. However, many species may not be able to keep pace with climate change, either because their seeds do not disperse widely or because they have limited mobility, thus leading, in some places, to local extinctions of both plants and animals. Both range shifts and local extinctions will, in many places, lead to large changes in the composition of plants and animals, resulting in new communities that bear little resemblance to those of today (Cheung et al. 2009; Lawler et al. 2009; Stralberg et al. 2009; USGS 2012; Wenger et al. 2011).

Some of the most obvious changes in the landscape are occurring at the boundaries between biomes. These include shifts in the latitude and elevation of the boreal forest/tundra boundary in Alaska (Beck et al. 2011; Dial et al. 2007; Lloyd and Fastie 2003; Suarez et al. 1999; Wilmking et al. 2004); elevational shifts of boreal and subalpine forest/tundra boundary in the Sierra Nevada, California (Millar et al. 2004); an elevational shift of temperate broadleaf/conifer boundary in the Green Mountains, Vermont (Beckage et al. 2008), the shift of temperate shrubland/conifer forest boundary in Bandelier National Monument, New Mexico (Allen and Breshears 1998), and upslope shifts of temperate mixed forest/conifer boundary in Southern California (Kelly and Goulden 2008). All of these are consistent with recent climatic trends and represent visible changes, like tundra switching to forest, or conifer forest switching to broadleaf forest or even to shrubland.

As temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, whitefish, and char) will be lost from lower-elevation streams, including a projected loss of 48% of habitat for all trout species in the western U.S. by 2080 (Wenger et al. 2011). Similarly, in the oceans, transitions from cold-water fish communities to warm-water communities have occurred in commercially important harvest areas (Lucey and Nye 2010; Wood et al. 2008), with new industries developing in response to the arrival of new species (McCay et al. 2011; Pinnegar et al. 2010). Also, warm surface waters are driving some fish species to deeper waters (Caputi et al. 2010; Dulvy et al. 2008; Nye et al. 2009; Perry et al. 2005).

Warming is likely to increase the ranges of several invasive plant species in the U.S. (Bradley et al. 2010), increase the probability of establishment of invasive plant species in boreal forests in south-central and Kenai, Alaska (Wolken et al. 2011), and expand the range of the hemlock wooly adelgid, an insect that has killed many eastern hemlocks in recent years (Albani et al. 2010; Dukes et al. 2009; Orwig et al. 2012; Paradis et al. 2008). Invasive species costs to the U.S. economy are estimated at $120 billion per year (Pimentel et al. 2005), including substantial impacts on ecosystem services. For instance, the wildland pest yellow star-thistle, which is predicted to thrive with increased atmospheric CO_2 (Dukes et al. 2011), currently costs California ranchers and farmers $17 million in forage and control efforts (Eagle et al. 2007) and $75 million in water losses (Gerlach 2004). Iconic desert species such as saguaro cactus and Joshua trees (Saunders et al. 2009) are damaged or killed by fires fueled by non-native grasses, leading to a large-scale transformation of desert shrubland into grassland in many of the familiar landscapes of the American West. Bark beetles have infested extensive areas of the western U.S. and Canada, killing stands of temperate and boreal conifer forest across areas greater than any other outbreak in the last 125 years (Raffa et al. 2008). Climate change has been a major causal factor, with higher temperatures allowing more beetles to survive winter, complete two life cycles in a season rather than one, and to move to higher elevations and latitudes (Bentz et al. 2010; Berg et al. 2006; Raffa et al. 2008). Bark beetle outbreaks in the Greater Yellowstone Ecosystem are outside the historic range of variability (Logan et al. 2010).

Seasonal Patterns

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, will shift, leading to important impacts on species and habitats.

Phenology, the pattern of seasonal life cycle events in plants and animals (such as timing of leaf-out, blooming, hibernation, and migration), has been called a "globally coherent fingerprint of climate change impacts" on plants and animals (Parmesan 2007; Parmesan and Yohe 2003; Root et al. 2003). Observed long-term trends towards shorter, milder winters and earlier spring thaws are altering the timing of critical spring events such as bud burst and emergence from overwintering. This can cause plants and animals to be so out of phase with their natural phenology that outbreaks of pests occur, or species cannot find food at the time they emerge.

Recent studies have documented an advance in the timing of springtime phenological events across species in response to increased temperatures (Network U.N.P. 2012). Long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures (Schwartz et al. 2006) and by 1.5 days per decade earlier in the western U.S. (Ault et al. 2011). Other multi-decadal studies for plant species have documented similar trends for early flowering (Cayan et al. 2001; Dunnell and Travers 2011; McEwan et al. 2011; Zhao and Schwartz 2003). In addition, plant-pollinator relationships may be disrupted by changes in the availability of nectar and pollen, as the timing of bloom shifts in response to temperature and precipitation (Aldridge et al. 2011; Forrest and Thomson 2011).

As spring is advancing and fall is being delayed in response to regional changes in climate (Beaubien and Hamann 2011; Huntington 2009; Jeong et al. 2011), the growing season is lengthening. A longer growing season will benefit some crops and natural species, but there may be a timing mismatch between the microbial activity that makes nutrients available in the soil and the readiness of plants to take up those nutrients for growth (Beaubien and Hamann 2011; Huntington 2009; Jeong et al. 2011; Muller and Bormann 1976). Where plant phenology is driven by day length, an advance in spring may exacerbate this mismatch, causing available nutrients to be leached out of the soil rather than absorbed and recycled by plants (Groffman et al. 2012). Longer growing seasons exacerbate human allergies. For example, a longer fall allows for bigger ragweed plants that produce more pollen later into the fall. (Rogers et al. 2006; Staudt et al. 2010).

Changes in the timing of springtime bird migrations are well-recognized biological responses to warming, and have been documented in the western (MacMynowski et al. 2007), Midwestern (MacMynowski and Root 2007), and eastern United States (Miller-Rushing et al. 2008; Van Buskirk et al. 2008). For example, some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds (Jones and Cresswell 2010). In a 34-year study of an

Alaskan creek, young pink salmon (*Oncorhynchus gorbuscha*) migrated to the sea increasingly early over time (Taylor 2008). In Alaska, warmer springs have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou (*Rangifer tarandus*).

Adaptation

Ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society.

Adaptation in the context of biodiversity and natural resource management is fundamentally about managing change, which is an inherent property of natural ecosystems (Staudinger et al. 2012; West et al. 2009; Link et al. 2010). One strategy, adaptive management, which is a structured process of flexible decision-making under uncertainty that incorporates learning from management outcomes, has received renewed attention as a tool for helping resource managers make decisions in response to climate change. Other strategies include assessments of vulnerability and impacts (Glick et al. 2011; Rowland et al. 2011), and scenario planning (Weeks et al. 2011), that can be assembled into a general planning process that is flexible, forward-thinking, and iterative.

Guidance on adaptation planning for conservation has proliferated at the federal (CEQ 2011a; EPA 2009; NOAA 2010; Peterson et al. 2011; Weeks et al. 2011) and state levels (AFWA 2009), and often emphasizes cooperation between scientists and managers (Cross et al. 2012; Halofsky et al. 2011; Peterson et al. 2011). Ecosystem-based adaptation (CBD 2010; Colls et al. 2009; The World Bank 2010; Vignola et al. 2009) uses "biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change" (CBD 2010). An example is the explicit use of storm-buffering coastal wetlands or mangroves rather than built infrastructure like seawalls or levies to protect coastal regions (Kershner 2010; Shaffer et al. 2009; Ch. 25 Coastal Zone). An additional example is the use of wildlife corridors (Chetkiewicz et al. 2006).

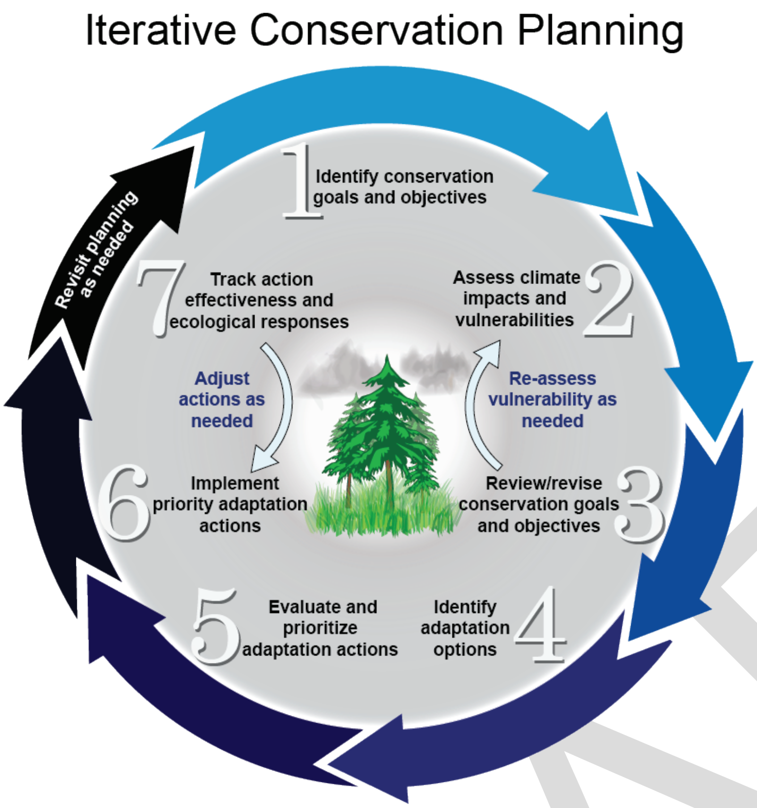

Figure 8.3: Iterative Conservation Planning

Caption: Iterative approaches to conservation planning require input and communication among many players to ensure flexibility in response to climate change (Figure source: Created for this report by Nancy B. Grimm of Arizona State University and by NOAA NCDC)

Adaptation strategies to protect biodiversity include: 1) habitat manipulations; 2) conserving populations with higher genetic diversity or more plastic behaviors or morphologies; 3) changing seed sources for re-planting to introduce species or ecotypes that are better suited for future climates; 4) assisted migration to help move species and populations from current locations to those areas expected to become more suitable in the future; and 5) ex-situ conservation such as seed banking, biobanking, and captive breeding (Cross et al. 2012; Halofsky et al. 2011; Peterson et al. 2011; Poiani et al. 2011; Weeks et al. 2011). Alternative approaches focus on identifying and protecting features that are important for biodiversity and are less likely to be altered by climate change. The idea is to conserve the "stage" (the physical conditions that contribute to high levels of biodiversity) for whatever "actors" (for example, species and populations) find those areas suitable in the future (Anderson and Ferree 2010; Beier and Brost 2010; Groves et al. 2012; Hunter et al. 1988).

Box 1. Case Study of the 2011 Las Conchas, New Mexico Fire
In the midst of severe drought in the summer of 2011, Arizona and New Mexico suffered the largest recorded wildfires in their history, affecting more than 694,000 acres. Some rare threatened and endangered species, like Mexican spotted owls and the Jemez salamander, were

devastated by the fire (NPS 2011). Following the fire, heavy rainstorms led to major flooding and erosion, including at least ten debris flows. Popular recreation areas were evacuated and floods damaged the newly renovated, multi-million dollar U.S. Park Service Visitor Center. Sediment and ash eroded by the floods were washed downstream into the Rio Grande, which supplies 50% of drinking water for Albuquerque, the largest city in New Mexico. Water withdrawals by the city from the Rio Grande were stopped entirely for a week and reduced for several months due to the increased cost of treatment.

These fires provide an example of how forest ecosystems, biodiversity, and ecosystem services are affected by the impacts of climate change, other environmental stresses, and past management practices. Higher temperatures, reduced snowpack, and earlier onset of springtime are leading to increases in wildfire in the western U.S. (Westerling et al. 2006), while extreme droughts are becoming more frequent (Williams et al. 2011). In addition, climate change is affecting naturally occurring bark beetles: warmer winter conditions allow these pests to breed more frequently and successfully (Jonsson et al. 2009; Schoennagel 2011) . The dead trees left behind by bark beetles make crown fires more likely (Hoffman et al. 2010; Schoennagel 2011). Forest management practices also have made the forests more vulnerable to catastrophic fires. In New Mexico, even-aged, second-growth forests were hit hardest because they are much denser than naturally occurring forest and consequently consume more water from the soil and increase the availability of dry above-ground fuel.

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Box 2

Biological Responses to Climate Change

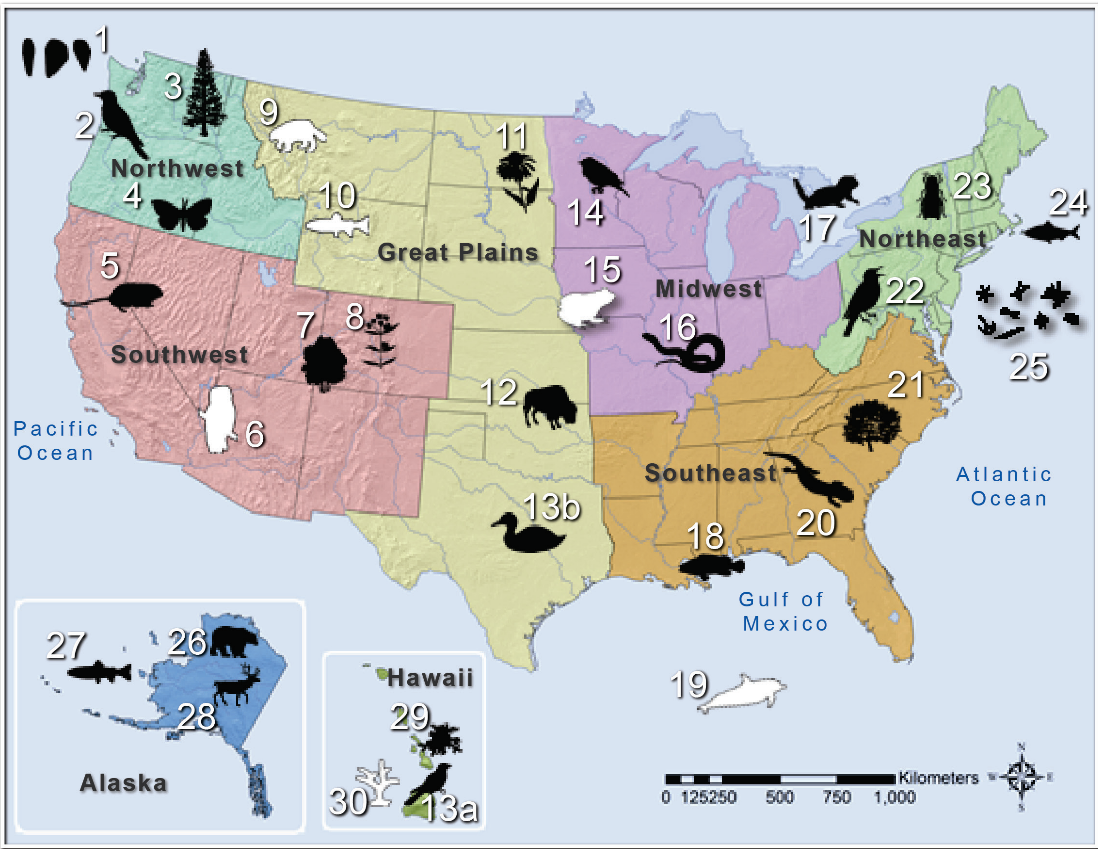

Figure 8.4: Biological Responses to Climate Change

Caption: Map of observed and projected biological responses to climate change across the United States. Case studies listed below correspond to observed responses (black icons on map) and *projected responses* (white icons on map, italicized statements). (Figure source: Adapted from Staudinger et al., 2012)

1. Mussel and barnacle beds have declined or disappeared along parts of Northwest coast (Harley 2011).
2. Northern flickers arrived at breeding sites earlier in Northwest in response to temperature changes along migration routes (Wiebe and Gerstmar 2010).
3. Conifer forests in many western forests have died from warming-induced changes in the prevalence of pests and pathogens (van Mantgem et al. 2009).
4. Butterflies that have adapted to specific oak species have not been able to colonize new tree species when climate change-induced tree migration changes local forest types (Pelini et al. 2010).

5. In response to climate-related habitat change, many small mammal species have altered their elevational ranges, with lower-elevation species expanding their ranges and higher-elevation species contracting their ranges (Moritz et al. 2008).

6. *Owl populations in Arizona and New Mexico are projected to decline during the next century and are at high risk for extinction due to future climatic changes, while the southern California population is not projected to be sensitive to future climatic changes* (Peery et al. 2012).

7. Quaking aspen-dominated systems are experiencing declines in the western U.S. after stress due to climate-induced drought conditions during the last decade (Anderegg et al. 2012).

8. Warmer and drier conditions during the early growing season in high elevation habitats in Colorado are disrupting the timing of various flowering patterns, with potential impacts on many important plant-pollinator relationships (Forrest and Thomson 2011).

9. *Population fragmentation of wolverines in the northern Cascades and Rocky Mountains is expected to increase as spring snow cover retreats over the coming century* (McKelvey et al. 2011).

10. *Cutthroat trout populations in the western U.S. are projected to decline by up to 58%, and total trout habitat in the same region is projected to decline by 48%, due to increasing temperatures, seasonal shifts in precipitation, and negative interactions with non-native species* (Wenger et al. 2011).

11. First flowering dates in 178 plant species from North Dakota have shifted significantly in more than 40% of all species examined (Dunnell and Travers 2011).

12. Variation in the timing and magnitude of precipitation was found to impact weight gain of bison in the Konza Prairie in Kansas and the Tallgrass Prairie Preserve in Oklahoma (Craine et al. 2008).

13. Increased environmental variation has been shown to influence mate selection and increase the probability of infidelity in birds that are normally socially monogamous to increase the gene exchange and the likelihood of offspring survival (Botero and Rubenstein 2012).

14. Migratory birds monitored in Minnesota over a 40-year period showed significantly earlier arrival dates, particularly in short-distance migrants, due to increasing winter temperatures (Swanson and Palmer 2009).

15. *The northern leopard frog is projected to experience poleward and elevational range shifts in response to climatic changes in the latter quarter of the century* (Lawler et al. 2010).

16. Studies of black ratsnake (*Elaphe obsoleta*) populations at different latitudes in Canada, Illinois, and Texas suggest that snake populations, particularly in the northern part of their range, could benefit from rising temperatures if there are no negative impacts on their habitat and prey (Sperry et al. 2010).

17. Warming-induced hybridization was detected between southern and northern flying squirrels in the Great Lakes region of Ontario Canada, and Pennsylvania after a series of warm winters created more overlap in their habitat range (Garroway et al. 2009).

18. Some warm-water fishes have moved northwards, and some tropical and subtropical fishes in the northern Gulf of Mexico have increased in temperate ocean habitat (Fodrie et al. 2009); Similar shifts and invasions have been documented in Long Island Sound and Narragansett Bay in the Northeast Atlantic (Wood et al. 2009).

19. *Global marine mammal diversity is projected to decline by as many as 11 species by mid-century, particularly in coastal habitats, due to climatic change* (Kaschner et al. 2011).

20. Higher nighttime temperatures and cumulative seasonal rainfalls were correlated with changes in the arrival times of amphibians to wetland breeding sites in South Carolina over a 30-year time period (1978-2008) (Todd et al. 2011).

21. Seedling survival for nearly 20 species of trees decreased during years of lower rainfall in the Southern Appalachians and the Piedmont areas (Ibáñez et al. 2008).

22. Widespread declines in body size of resident and migrant birds at a bird-banding station in western Pennsylvania were documented over a 40-year period; body sizes of breeding adults were negatively correlated with mean regional temperatures from the preceding year (Van Buskirk et al. 2009).

23. Over the last 130 years (1880-2010), native bees have advanced their spring arrival in the northeastern U.S. by an average of 10 days, primarily due to increased warming. Plants have also showed a trend of earlier blooming, thus helping preserve the synchrony in timing between plants and pollinators (Bartomeus et al. 2011).

24. In the Northwest Atlantic, 24 out of 36 commercially exploited fish stocks showed significant range (latitudinal and depth) shifts between 1968–2007 in response to increased sea surface and bottom temperatures (Nye et al. 2009).

25. Increases in maximum and decreases in the annual variability of sea surface temperatures in the North Atlantic Ocean have promoted growth of small phytoplankton and led to a reorganization in the species composition of primary (phytoplankton) and secondary (zooplankton) producers (Beaugrand et al. 2010).

26. Changes in female polar bear reproductive success (decreased litter mass, and numbers of yearlings) along the north Alaska coast have been linked to changes in body size and/or body condition following years with lower availability of optimal sea ice habitat (Rode et al. 2010).

27. Water temperature data and observations of migration behaviors over a 34-year time period showed that adult pink salmon migrated earlier into Alaskan creeks, and fry advanced the timing of migration out to sea. Shifts in migration timing may increase the potential for a mismatch in optimal environmental conditions for early life stages, and continued warming trends will likely increase pre-spawning mortality and egg mortality rates (Taylor 2008).

28. Warmer springs in Alaska have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou. This ultimately reduced calving success in caribou populations (Post et al. 2008).

29. Many Hawai'ian mountain vegetation types were found to vary in their sensitivity to changes in moisture availability; consequently, climate change will likely influence elevational patterns in vegetation in this region (Crausbay and Hotchkiss 2010).

30. *A 1.6 to 3.3 foot local sea level rise in Hawai'ian waters, consistent with global projections of 1 to 4 feet of sea level rise (see Ch. 2: Our Changing Climate, Key Message 9) is projected to increase wave heights, the duration of turbidity, and the amount of re-suspended sediment in the water; consequently, this will create potentially stressful conditions for coral reef communities* (Cardinale et al. 2012; Hooper et al. 2012; Storlazzi et al. 2011)

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Traceable Accounts

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: The key messages and supporting chapter text summarize extensive evidence documented in the Ecosystems Technical Input, *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment,* Michelle D. Staudinger, Nancy B. Grimm, Amanda Staudt, Shawn L. Carter, F. Stuart Chapin III, Peter Kareiva, Mary Ruckelshaus, Bruce A. Stein. (2012). This foundational report evolved from a technical workshop held at the Gordon and Betty Moore Foundation in Palo Alto, CA, in January 2012 and attended by approximately 65 scientists. Technical inputs (127) on a wide range of topics related to ecosystems were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Key message #1/5	**Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.**
Description of evidence base	The author team digested the contents of over 125 technical input reports on a wide array of topics to arrive at this key message. The foundational USGS report was the primary source used. Studies have shown that increasing precipitation is already resulting in declining water quality in many regions of the country, particularly by increasing nitrogen loading (Howarth et al. 2012; Howarth et al. 2006; Justic et al. 2005; McIsaac et al. 2002; Sobota et al. 2009). This is because the increases in flow can pick up and carry greater loads of nutrients like nitrogen to rivers. One model for the Mississippi River basin, based on a doubling of CO_2, projects that increasing discharge and nitrogen loading will lead to larger algal blooms in the Gulf of Mexico and a larger dead zone (Justic et al. 1996). The Gulf of Mexico is the recipient system for the Mississippi basin, receiving all of the nitrogen that is carried downriver but not removed by wetlands, river processes, or other ecosystems. Several models project that declining streamflow, due to the combined effects of climate change and water withdrawals, will cause local extinctions of fish and other aquatic organisms (Spooner et al. 2011; Xenopoulos et al. 2005), particularly trout in the interior West (composite of 10 models, A1B scenario) (Wenger et al. 2011). This is one of the few studies of impacts on fish that uses an emissions scenario and a combination of climate models. The researchers studied four different trout species and although there were variations among species, their overall conclusion was robust across species for the composite model. Water quality can also be negatively affected by increasing temperatures. There is widespread evidence that warmer lakes can promote the growth of harmful algal blooms, which produce toxins (Paerl and Huisman 2008).
New information and remaining uncertainties	Recent research has improved understanding of the relative importance of the effects of climate and human actions (for example, fertilization) on nitrogen losses from watersheds (Howarth et al. 2012; Sobota et al. 2009), and how the interactions between climate and human actions (for example, water withdrawals) will affect fish populations in the west (Spooner et al. 2011, Wenger et al. 2011). However, few studies have projected the impacts of future climate change on water quality. Given the tight link between river discharge and pollutants, only areas of the U.S. that are projected to see increases in precipitation will see increases in pollutant transport to rivers. It is also important to note that pollutant loading, for example, nitrogen fertilizer use, is often more important as a driver of water pollution than climate (Howarth et al. 2012; Sobota et al. 2009).

Assessment of confidence based on evidence	Given the evidence base and uncertainties, there is **high** confidence that climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows. It is well established that precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) transport into rivers. Increases in precipitation in many regions of the country are therefore contributing to declines in water quality in many areas. However, those areas of the country that will see reduced precipitation may experience water-quality improvement; thus, any lack of agreement on future water-quality impacts of climate change is likely due to locational differences.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #2/5	**Climate change combined with other stressors is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms**
Description of evidence base	**Fires:** Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires"—large fires that are unprecedented in their social, economic and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 million (Hedde 2012) . **Floods:** Salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against storm surges, and their losses from coastal development, erosion, and sea-level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (see Chap 25: Coastal Zone, Development and Ecosystems) (FitzGerald et al. 2008; McGranahan et al. 2007). Floodplain wetlands, although greatly reduced from their historical extent, absorb floodwaters and reduce the impact of high flows on river-margin lands. Where they are lost to inundation, the consequences would be profound. In the Northeast, even a small sea-level rise (1.6 ft, which is expected by 2080) will dramatically increase impacts of storm surge on people (47% increase) and property loss (73% increase) in Long Island (Shepard et al. 2012). **Storms:** Extreme weather events that produce sudden increases in water flow and the materials it carries can decrease the natural capacity of ecosystems to process pollutants, both by reducing the amount of time water is in contact with reactive sites and by removing or harming the plants and microbes that remove the pollutants (FitzGerald et al. 2008; McGranahan et al. 2007; Ch. 25 Coastal Zone).
New information and remaining uncertainties	A new analytical framework was recently developed to generate insights into the interactions among the initial state of ecosystems, the type and magnitude of disturbance, and effects of disturbance (Peters et al. 2011). Progress in understanding these relationships is critical for predicting how human activities and climate change, including extreme events like droughts, floods, and storms, will interact to effect ecosystems, and how ecosystems will respond. Uncertainties: The ability of ecosystems to buffer extreme events is extremely difficult to assess and quantify, as it requires understanding of complex ecosystem response to very rare events. However, it is clear that the loss of this buffering ecosystem service is having important effects on coastal and fire-prone ecosystems across the U.S.
Assessment of confidence based on evidence	Give the evidence base and uncertainties, there is **high** confidence that climate change combined with other stressors is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like droughts, floods, and storms. Salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against storm surges, but their losses from coastal development, erosion, and sea level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (FitzGerald et al.

	2008; McGranahan et al. 2007). Whether salt marshes and mangroves will be able to accrue sediment at rates sufficient to keep ahead of sea level rise and maintain their protective function will vary by region (Blum and Roberts 2009; Craft et al. 2009; Gedan et al. 2011; Stralberg et al. 2011). Climate has been the dominant factor controlling burned area during the 20th century, even during periods of fire suppression by forest management (Littell et al. 2009; Miller et al. 2011; Westerling et al. 2006; Westerling et al. 2011), and the area burned annually has increased steadily over the last 20 years concurrent with warming and/or drying climate (Morton 2012). Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 million (Hedde 2012).

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #3/5	**Land- and sea-scapes are changing rapidly and species, including many iconic species, may disappear from regions where they have been prevalent, changing some regions so much that their mix of plant and animal life will become almost unrecognizable.**
Description of evidence base	The analysis for the technical input report applied a range of future climate scenarios and projected biome changes across 5% to about 20% of the land area in the U.S. by 2100 (USGS 2012b). Other analyses support these projections (Alo and Wang 2008; Bergengren et al. 2011; Gonzalez et al. 2010; Sitch et al. 2008). Studies predict that wildfire will be a major driver of change in some areas, including Yellowstone Nation Park (Westerling et al. 2011) and the Arctic (Hu et al. 2010). These biomes shifts will be associated with changes in species distributions (Chen et al. 2011). Evidence indicates that the most obvious changes will occur at the boundaries between ecosystems (Allen and Breshears 1998; Beck et al. 2011; Beckage et al. 2008; Dial et al. 2007; Kelly and Goulden 2008; Lloyd and Fastie 2003; Millar et al. 2004; Suarez et al. 1999; Wilmking et al. 2004). Plants and animals are already moving to higher elevations and latitudes in response to climate change (Chen et al. 2011), with models projecting greater range shifts (Munson et al. 2012; Stralberg et al. 2009; Wenger et al. 2011) and local extinctions in the future, leading to new plant and animal communities that may be unrecognizable in some regions (Cheung et al. 2009; Lawler et al. 2009; Stralberg et al. 2009; USGS 2012b). For fish, Wenger et al. (2011) used general circulation models (GCMs) simulating conditions in the 2040s and 2080s under the A1B emissions scenario, with the choice of models reflecting predictions of high and low climate warming as well as an ensemble of ten models. Their models additionally accounted for biotic interactions. Stralberg et al. (2009) used a 30-year baseline (1971-2000) and output from two GCMs under the A2 scenario to develop biologically meaningful climate variables for present and future predictions of species ranges. Munson et al. used empirical data from the Sonoran Desert (n=39 plots) to evaluate species responses to past climate variability. **Iconic species:** Wildfire is expected to damage and kill iconic desert species, including saguaro cactus and Joshua trees (Saunders et al. 2009), while bark beetle outbreaks, which have been exacerbated by climate change, are damaging extensive areas of temperate and boreal conifer forests that are characteristic of western U.S. (Raffa et al. 2008).
New information and remaining uncertainties	In addition to the technical input report, over 20 new studies of observed and predicted effects of climate change on biomes and species distribution were incorporated in the assessment. While changes in ecosystem structure and biodiversity, including the distribution of iconic species, are occurring and are highly likely to continue, the impact of these changes on ecosystem services is unclear, that is, there is uncertainty about the impact that loss of familiar landscapes will have on people.
Assessment of confidence based on evidence	Based on the evidence base and uncertainties, confidence is **high** that familiar landscapes are changing so rapidly that iconic species may disappear from regions where they have been prevalent, changing some regions so much that their mix of plant and animal life will become almost unrecognizable. Many changes in species distribution have already occurred and will inevitably continue, resulting in the loss of familiar landscapes and the production of novel species assemblages.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #4/5	**Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, will shift, leading to important impacts on species and habitats.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Ecosystems Technical Input (Phenology as a bio-indicator of climate change impacts on people and ecosystems: towards an integrated national assessment approach. A Technical Input to the 2013 National Climate Assessment Report., (2012), USA-NPN National Coordinating Office: Tucson, AZ.). An additional 127 input reports, on a wide range of topics related to ecosystems, were also received and reviewed as part of the Federal Register Notice solicitation for public input. Many studies have documented an advance in springtime phenological events of species in response to climate warming. For example, long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures, and by 1.5 days per decade earlier in the western U.S. (Ault et al. 2011; Schwartz et al. 2006). Other multi-decadal studies for plant species have documented similar trends for early flowering (Cayan et al. 2001; Dunnell and Travers 2011; McEwan et al. 2011; Zhao and Schwartz 2003). Evidence suggests that insect emergence from overwintering may become out of sync with pollen sources (Forrest and Thomson 2011), and that the beginning of bird and fish migrations are shifting (Jones and Cresswell 2010; MacMynowski and Root 2007; MacMynowski et al. 2007; Miller-Rushing et al. 2008; Taylor 2008; Van Buskirk et al. 2009).
New information and remaining uncertainties	In addition to the Ecosystems Technical Input (Phenology as a bio-indicator of climate change impacts on people and ecosystems: towards an integrated national assessment approach. A Technical Input to the 2013 National Climate Assessment Report., (2012), USA-NPN National Coordinating Office: Tucson, AZ.), many new studies have been conducted since the previous assessment, contributing to our understanding of the impacts of climate change on phonological events. A key uncertainty is "phase effects" where organisms are so out of phase with their natural phenology that outbreaks of pests occur, species emerge and cannot find food, or pollination is disrupted. This will vary with specific species and is therefore very difficult to predict.
Assessment of confidence based on evidence	Given the evidence base and uncertainties, there is **very high** confidence that the timing of critical events, such as spring bud burst, emergence from overwintering, and the start of migrations, will shift leading to important impacts on species and habitats. Many studies, in many areas have shown significant changes in phenology, including spring bud burst, emergence from overwintering, and migration shifts.

CONFIDENCE LEVEL			
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Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #5/5	**Ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society.**
Description of evidence base	Guidance on adaptation planning for conservation has proliferated at the federal (CEQ 2011a; EPA 2009; NOAA 2010; Peterson et al. 2011; Weeks et al. 2011) and state levels (AFWA 2009), and often emphasizes cooperation between scientists and managers (Cross et al. 2012; Halofsky et al. 2011; Peters et al. 2011; Peterson et al. 2011). Ecosystem-based adaptation (CBD 2009, Colls et al. 2009, Vignola et al. 2009, World Bank 2010) uses “biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change” (CBD 2010). An example is the explicit use of storm-buffering coastal wetlands or mangroves rather than built infrastructure like seawalls or levies to protect coastal regions (Kershner 2010; Shaffer et al. 2009; Ch. 25 Coastal Zone);(See also Ch. 25: Coastal Zone).
New information and remaining uncertainties	Adaptation strategies to protect biodiversity include include: 1) habitat manipulations; 2) conserving populations with higher genetic diversity or more plastic behaviors or morphologies; 3) changing seed sources for re-planting to introduce species or ecotypes that are better suited for future climates; 4) assisted migration to help move species and populations from current locations to those areas expected to become more suitable in the future; and 5) ex-situ conservation such as seed banking and captive breeding (Cross et al. 2012; Halofsky et al. 2011; Peterson et al. 2011; Poiani et al. 2011; Weeks et al. 2011). Alternative approaches focus on identifying and protecting features that are important for biodiversity and are less likely to be altered by climate change. The idea is to conserve the “stage” (the physical conditions that contribute to high levels of biodiversity) for whatever “actors” (for example, species and populations) find those areas suitable in the future (Anderson and Ferree 2010; Beier and Brost 2010; Groves et al. 2012; Hunter et al. 1988).
Assessment of confidence based on evidence	Given the evidence and remaining uncertainties, there is **very high** confidence that ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society. The effectiveness of these actions is much less certain however.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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9. Human Health

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Key Messages:

1. **Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, diseases transmitted by insects, food and water, and threats to mental health. Some of these health impacts are already underway in the U.S.**
2. **Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.**
3. **Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.**
4. **Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.**

Climate change, together with other natural and human-made health stressors, will influence human health and disease in many ways, regardless of whether prevention and adaptation efforts are undertaken. Evidence indicates that, absent these other changes (prevention/adaptation activities, infrastructure improvements) and with increasing population susceptibilities (aging, limited economic resources, etc.), some existing health threats will intensify and new health threats will emerge. Climate change is a global public health problem, with serious health impacts predicted to manifest in varying ways in different parts of the world. Public health in the U.S. can be affected by disruptions of physical, biological, and ecological systems elsewhere.

The health impacts of climate change will be highly variable. Key drivers of health impacts include: increasingly frequent and intense extreme heat, which also worsens drought and wildfire risks as well as air pollution; increasingly frequent extreme precipitation and associated flooding (see Ch. 2: Our Changing Climate); and rising sea levels that intensify coastal flooding and storm surge (see Ch. 25: Coastal Zone Development and Ecosystems). Key drivers of vulnerability include attributes of people (age, socioeconomic status, race) and of place (floodplain, coastal zone, urban areas), as well as the resilience of critical public health infrastructure.

Wide-ranging Health Impacts

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, diseases transmitted by insects, food and water, and threats to mental health. Some of these health impacts are already underway in the U.S.

Air Pollution

Climate change alone is projected to increase summertime ozone concentrations by 1 to 10 parts per billion this century (Bell et al. 2008; Chang et al. 2010; Ebi and McGregor 2008; EPA 2009; Post et al. 2012; Spickett et al. 2011; Tagaris et al. 2007). Ground-level ozone is associated with diminished lung function, increased hospital admissions and emergency room visits, and increases in premature mortality (Dennekamp and Carey 2010; Kampa and Castanas 2008; Kinney 2008). Current estimates suggest that 1,000 premature deaths per 1.8°F rise in temperature could occur each year related to worsened ozone and particle pollution (Ebi and McGregor 2008; Jacob and Winner 2009; Jacobson 2008; Kinney 2008; Liao et al. 2009; Spickett et al. 2011). Other studies project 4,300 additional premature deaths per year by 2050 (Russell et al. 2010; Tagaris et al. 2009). Health-related costs of climate change's current effects on ozone air pollution have been estimated at \$6.5 billion nationwide (Knowlton et al. 2011; Östblom and Samakovlis 2007).

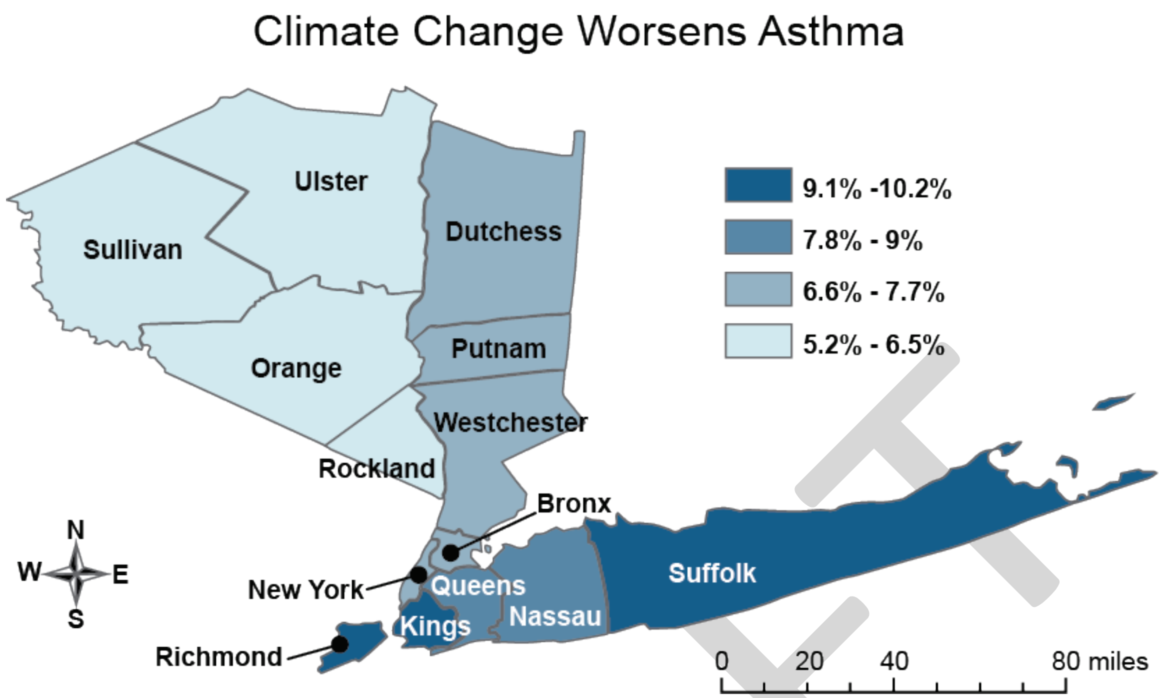

Figure 9.1: Climate Change Worsens Asthma

Caption: Percentage increases in emergency room visits for asthma related to ground-level ozone among children in the New York City region by the 2020s, resulting from the effects of climate change. Asthma accounts for one-quarter of all emergency room visits in the U.S. – 1.75 million each year. Costs for this chronic disease increased from an estimated $53 billion in 2002 to about $56 billion in 2007. In 2010, an estimated 25.7 million Americans had asthma, which has become a problem in every state. The condition is distinctly prevalent in California's Central Valley, where one out of every six children has asthma symptoms. (Sheffield et al. 2011b)

Allergens

Climate change can contribute to increased production of plant-based allergens (Emberlin et al. 2002; Pinkerton et al. 2012; Schmier and Ebi 2009; Shea et al. 2008; Sheffield and Landrigan 2011c; Sheffield et al. 2011b; Ziska et al. 2011). Higher pollen concentrations and longer pollen seasons increase allergic sensitizations and asthma episodes (Ariano et al. 2010; Breton et al. 2006; EPA 2008; Perry et al. 2011) and diminish productive work and school days (Sheffield et al. 2011a; Staudt et al. 2010; Ziska et al. 2011). Simultaneous exposure to air pollutants can worsen allergic responses (D'amato and Cecchi 2008; D'amato et al. 2010; Reid and Gamble 2009). Extreme rainfall and rising temperatures can also foster the growth of indoor fungi and molds, with increases in respiratory and asthma-related conditions (Fisk et al. 2007; IOM 2011; Mudarri and Fisk 2007; Wolf et al. 2010).

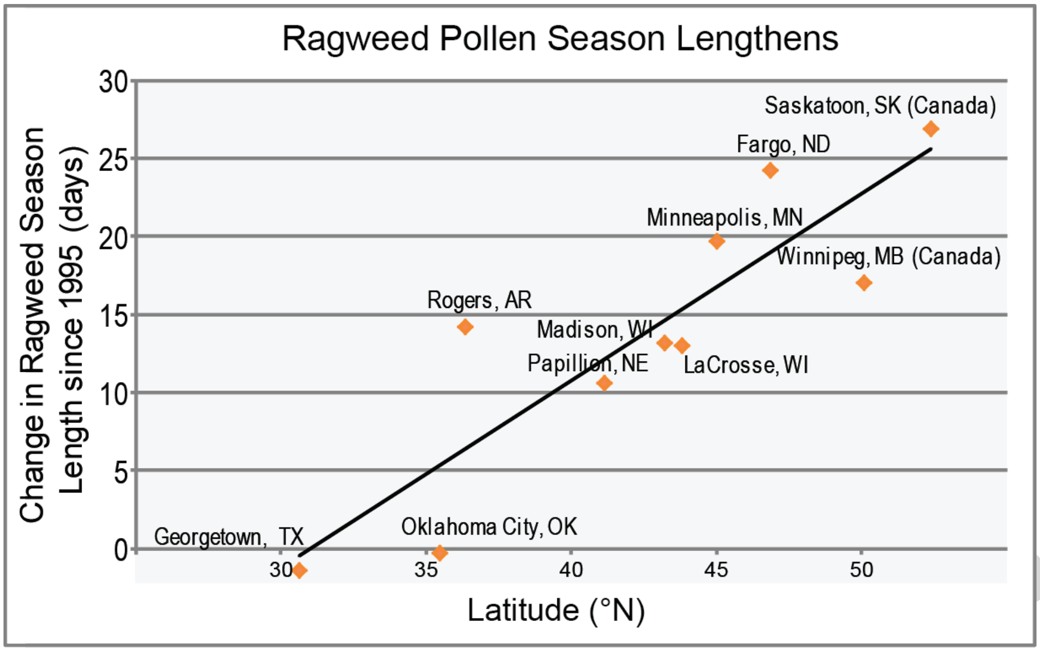

Figure 9.2: Ragweed Pollen Season Lengthens

Caption: Ragweed pollen season length has increased in central North America between 1995 and 2011, by as much as 13 to 27 days in parts of the U.S., in response to rising temperatures Increases in the length of this allergenic pollen season are correlated with increases in the number of days before the first frost. As shown on the graph, the largest increases have been observed in northern cities. In 2012, a "perfect storm" of pollen-producing conditions across much of the U.S. – a warm winter leading to early pollen production among trees and plants, followed by hot, dry, low-humidity conditions through the spring and summer – contributed to wide circulation of aeroallergens and, "a horrendous year" for allergies, according to physicians. Additional data provided by L. Ziska. (Sources: EPA 2008; Fears 2012; Irfan 2012; Perry et al. 2011; Ziska 2011)

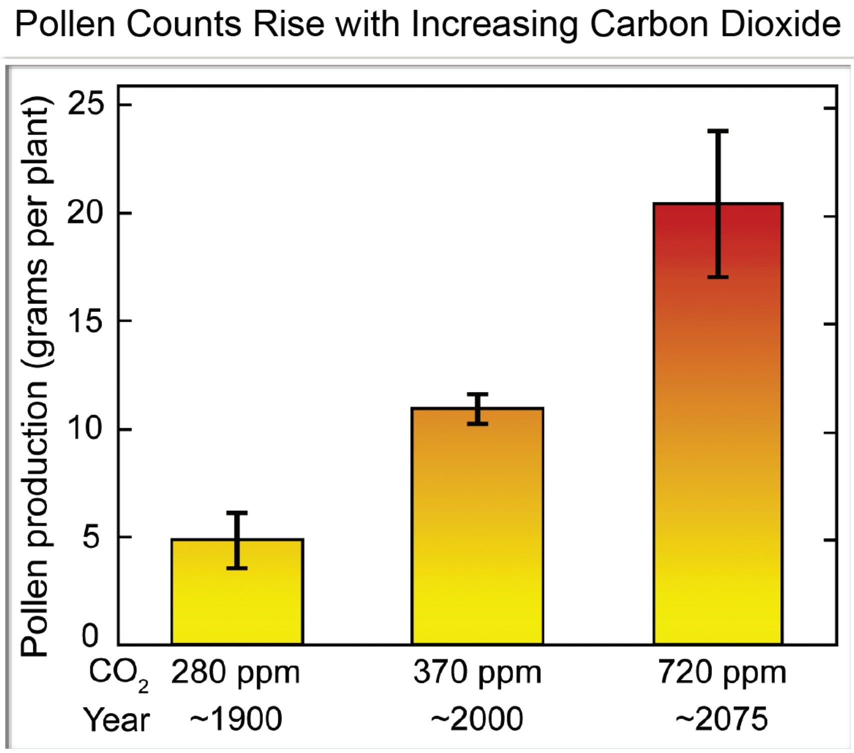

Figure 9.3: Pollen Counts Rise with Increasing Carbon Dioxide

Caption: Pollen production from ragweed grown in chambers at the carbon dioxide concentration of a century ago was about 5 grams per plant; at today's approximate carbon dioxide level, it was about 10 grams, and at a level projected to occur about 2075 under the higher emissions scenario (A2), it was about 20 grams. (Source: Ziska and Caufield 2000a).

Figure 9.4

Caption: Ragweed plant (Photo credit: Lewis Ziska/USDA)

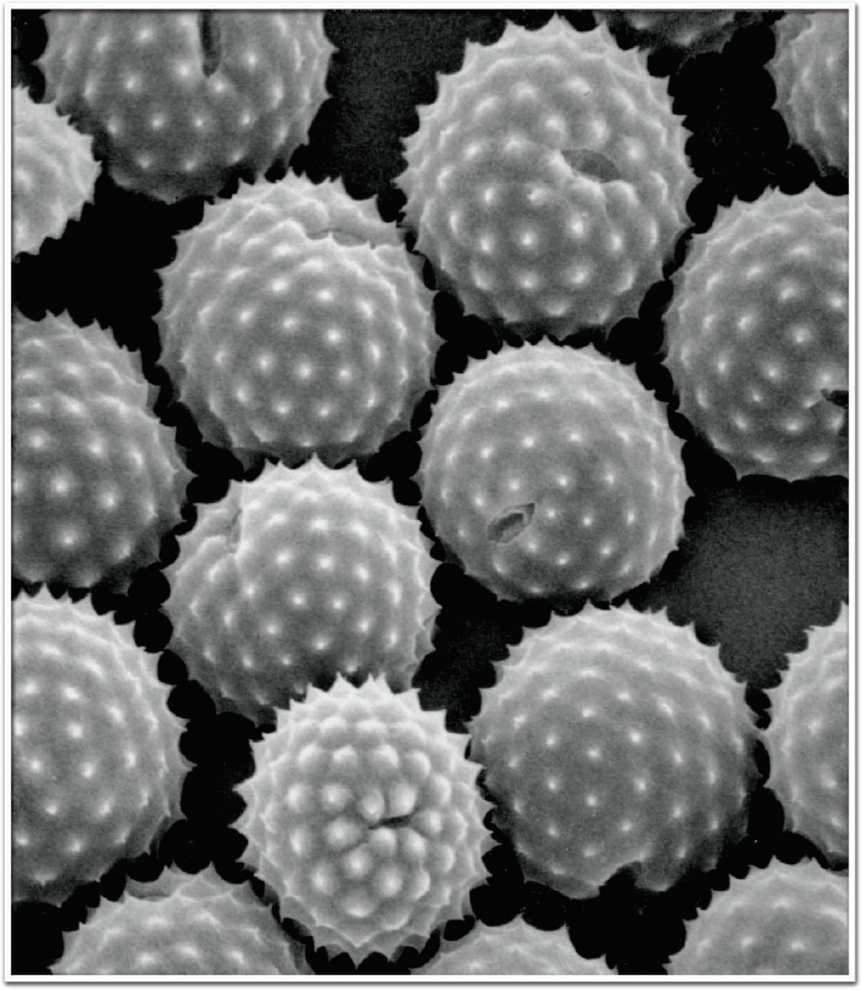

Figure 9.5

Caption: One ragweed plant can produce one billion grains (Rees 1997; Staudt et al. 2010) of allergenic pollen over a season, making it a prime culprit in harming health as temperatures and carbon dioxide levels rise under a changing climate. (Figure source: Lewis Ziska, USDA)

Wildfires

Climate change has already contributed to increasing wildfire frequency (Littell et al. 2009; Mills 2009; Shea et al. 2008; Westerling et al. 2006; Westerling et al. 2011). Wildfire smoke contains particulate matter, carbon monoxide, nitrogen oxides, and various volatile organic compounds (which are ozone precursors) (Akagi et al. 2011) and can significantly reduce air quality, both locally and in areas downwind of fires (Dennekamp and Abramson 2011; Jaffe et al. 2008a; Jaffe et al. 2008b; Pfister et al. 2008; Spracklen et al. 2007). Smoke exposure increases respiratory and cardiovascular hospitalizations, emergency department visits for asthma, bronchitis, chest pain, chronic obstructive pulmonary disease, respiratory infections, and medical visits for lung illnesses, and has been associated with hundreds of thousands of global deaths annually (Delfino et al. 2009; Dennekamp and Abramson 2011; Jenkins et al. 2009; Johnston et al. 2012; Lee et al. 2009). Future climate change is projected to contribute to wildfire risks and associated emissions, with harmful impacts on health (Jacob and Winner 2009; McDonald et al. 2009; Shea et al. 2008; Westerling and Bryant 2008).

Smoke from Wildfires has Widespread Health Effects

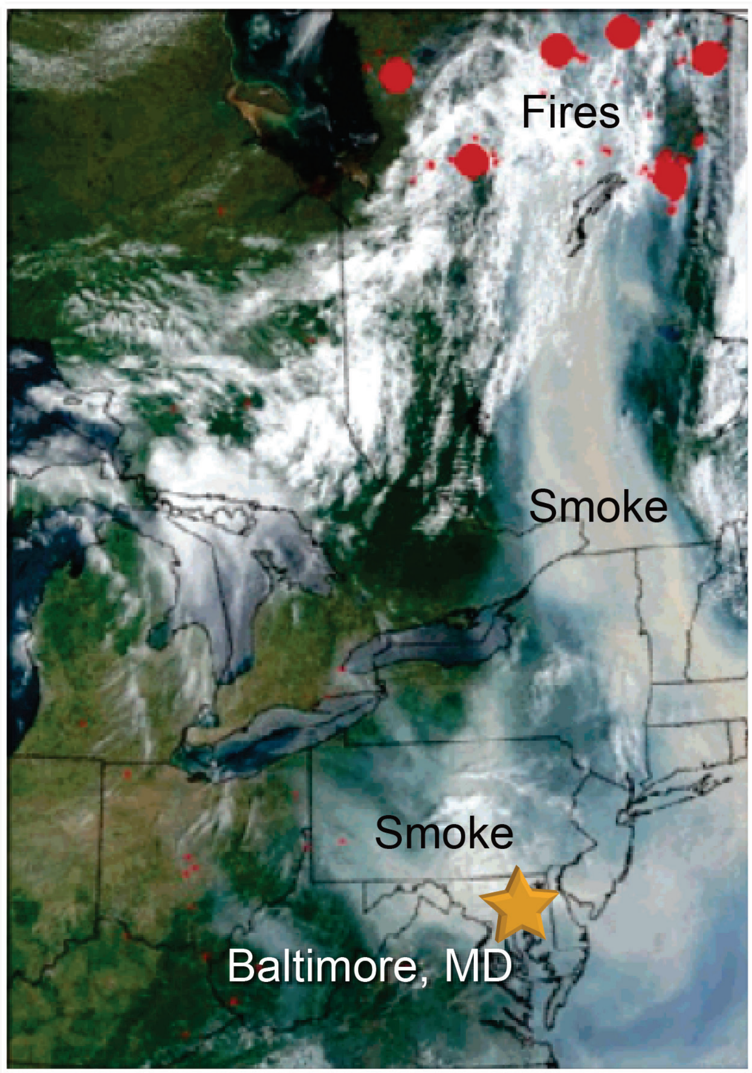

Figure 9.6: Smoke from Wildfires has Widespread Health Effects

Caption: Wildfires, which are increasing in part due to climate change, have health impacts that can extend thousands of miles. Shown here, forest fires in Quebec, Canada during July 2002 resulted in up to a 30-fold increase in airborne fine particle concentrations in Baltimore, Maryland, a city nearly a thousand miles downwind. These fine particles, which are extremely harmful to human health, not only effect outdoor air quality, but also penetrate indoors (median indoor-to-outdoor ratio 0.91), increasing the long-distance effects of fires on health. The 2012 wildfire season, at almost 9.2 million acres burned, is exceeded only by U.S. wildfires in 2006 when over 9.5 million acres went up in smoke (NCDC 2012). Estimated global deaths from landscape fire smoke have been estimated at 260,000 to 600,000 annually (Johnston et al. 2012). (Source: Kinney (2008). ORIGINAL SOURCE: Sapkota, et al. (2005))

Temperature Extremes

Extreme heat events have long threatened public health in U.S. metropolitan areas (Anderson and Bell 2011; Åström et al. 2011; Ye et al. 2012; Zanobetti et al. 2012). Many cities, including St. Louis, Philadelphia, Chicago, and Cincinnati have sustained dramatic increases in death rates following heat waves. Deaths result from heat stroke and related conditions (Åström et al. 2011; Huang et al. 2011; Li et al. 2012; Ye et al. 2012; Zanobetti et al. 2012), but also from cardiovascular disease, respiratory disease, and cerebrovascular disease (Basu 2009; Rey et al. 2007). Heat waves are also associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders (Knowlton et al. 2009; Lin et al. 2009; Nitschke et al. 2011; Ostro et al. 2009; Rey et al. 2007). Extreme summer heat is increasing in the U.S. (Duffy and Tebaldi 2012; Ch. 2: Our Changing Climate; Key Message 7), and climate projections indicate that extreme heat events will be more frequent and intense in coming decades (Hayhoe et al. 2010; IPCC 2007; Jackson et al. 2010; Ch. 2: Our Changing Climate; Key Message 7).

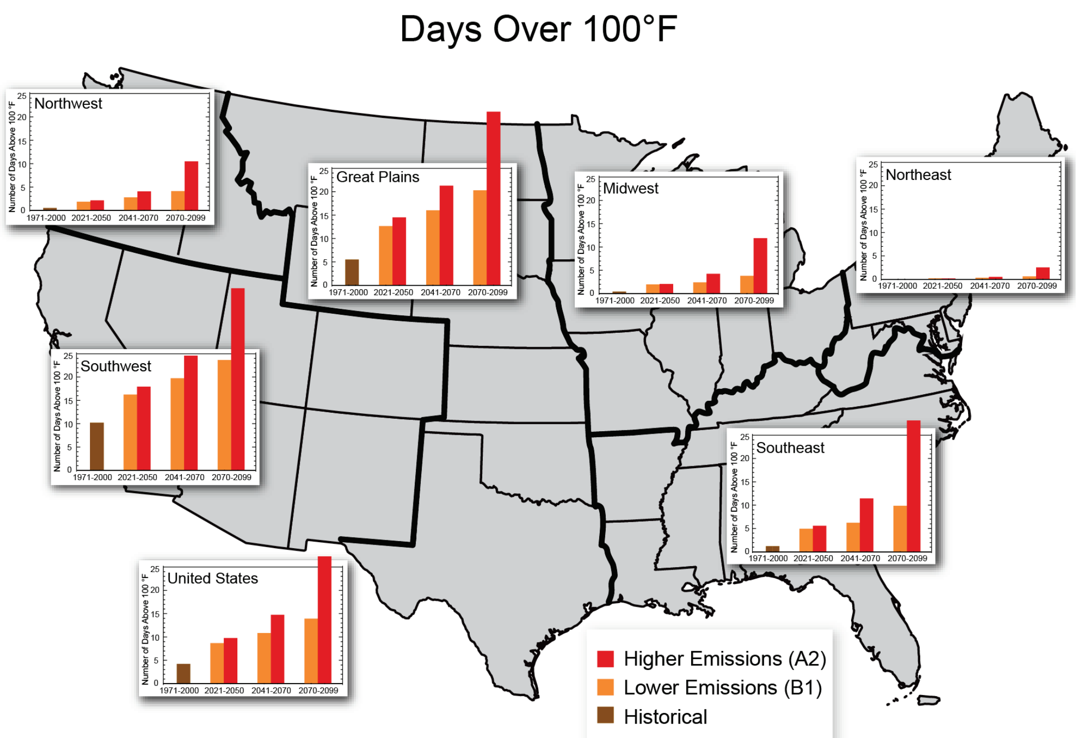

Figure 9.7: Days Over 100°F

Caption: Projected numbers of summer days per year (regional averages) with temperatures greater than 100°F under a lower-emissions scenario in which emissions of heat-trapping gases are substantially reduced (B1) and a higher-emissions scenario in which emissions continue to grow (A2). Historical data are for 1971-2000 (farthest left bar in plots). Projections shown are 30-year averages centered on 2035, 2055, and 2085 (bars left to right). Historical data and projections are data from CMIP3. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Statistically Downscaled.)

Some of the risks of heat-related morbidity and mortality have diminished in recent decades, possibly due to better forecasting, heat-health early warning systems, and/or increased access to air conditioning for the U.S. population (Barnett 2007; Kalkstein et al. 2011). However, urban heat islands, combined with an aging population and increased urbanization, are projected to increase the vulnerability of urban populations to heat-related health impacts in the future (Johnson et al. 2009; Wilby 2008).

Milder winters resulting from a warming climate can reduce illness, accidents, and deaths associated with cold and snow. Vulnerability to winter weather depends on many non-climate factors, including housing, age, and baseline health (Anderson and Bell 2009; McMichael et al. 2008). While deaths and injuries related to extreme winter weather, such as extreme snow events and ice storms, are projected to decline due to climate change, these reductions are not expected to compensate for the increase in heat-related deaths (Medina-Ramón and Schwartz 2007; Yu et al. 2011).

Extreme Events, Injuries, and Illnesses

The frequency of heavy precipitation events has already increased across the U.S. and is projected to continue to increase (IPCC 2007). Both extreme precipitation and total precipitation have contributed to increases in severe flooding events (see Ch.2: Our Changing Climate). Floods are the second deadliest of all weather-related hazards in the U.S., accounting for approximately 98 deaths per year (Ashley and Ashley 2008), most due to drowning (NOAA 2010). Flash floods and flooding associated with tropical storms result in the highest number of deaths (Ashley and Ashley 2008).

In addition to the immediate health hazards associated with extreme precipitation events, other hazards can often appear once a storm event has passed. Waterborne diseases typically present in the weeks following inundation (Teschke et al. 2010), and water intrusion into buildings, can result in mold contamination that manifests later. Buildings damaged during hurricanes are especially susceptible to water intrusion. Those living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms, such as coughing and wheezing (Mendell et al. 2011). See “Heavy Downpour Links to Disease” figure below.

Diseases Carried by Insects and Rodents

The influence of climate change in altering the distribution of diseases borne by insects and rodents remains uncertain. The geographic and seasonal distribution of insect populations, and the diseases they can carry, depend not only on climate, but on land use, socioeconomic and cultural factors, insect control, access to health care, and human responses to disease risk, among other factors (Gage et al. 2008; Hess et al. 2012; Lafferty 2009; Wilson 2009). Climate variability on daily, seasonal, or year-to-year scales can sometimes result in insect/pathogen adaptation and shifts or expansions in their geographic ranges (Lafferty 2009; McGregor 2011; Wilson 2009). Such shifts can alter disease incidence depending on insect-host interaction, host immunity, and pathogen evolution (Epstein 2010; Reiter 2008; Rosenthal 2009; Russell 2009).

North Americans are currently at risk from numerous insect-borne diseases, including Lyme (Diuk-Wasser et al. 2010; Keesing et al. 2009; Mills et al. 2010; Ogden et al. 2008), dengue fever (Degallier et al. 2010; Johansson et al. 2009; Jury 2008; Kolivras 2010; Lambrechts et al.

2011; Ramos et al. 2008), West Nile virus (Gong et al. 2011; Morin and Comrie 2010), and Rocky Mountain spotted fever (Centers for Disease Control and Prevention 2010); invasive insect-borne pathogens, such as chikungunya, Chagas disease, and Rift Valley fever viruses are also threats. Whether higher winter temperatures in the U.S. will create better conditions for locally acquired transmission of diseases like malaria is uncertain, due to infrastructure such as air-conditioning that provides barriers to human-insect contact. Climate change-increased risk in countries where insect-borne diseases are commonly found can also increase susceptibility of North Americans, considering increasing trade with, and travel to, tropical and subtropical areas (McGregor 2011; Wilson 2009).

Box: Transmission Cycle of Lyme Disease

The development and survival of blacklegged ticks, their animal hosts, and the Lyme disease bacterium, *B. burgdorferi*, are strongly influenced by climatic factors, especially temperature, precipitation, and humidity. Potential impacts of climate change on the transmission of Lyme disease include: 1) changes in the geographic distribution of the disease due to the increase in favorable habitat for ticks to survive off their hosts; 2) a lengthened transmission season due to earlier onset of higher temperatures in the spring and later onset of cold and frost; 3) higher tick densities leading to greater risk in areas where the disease is currently observed due to milder winters and potentially larger rodent host populations; and 4) changes in human behaviors, including increased time outdoors, which may increase the risk of exposure to infected ticks.

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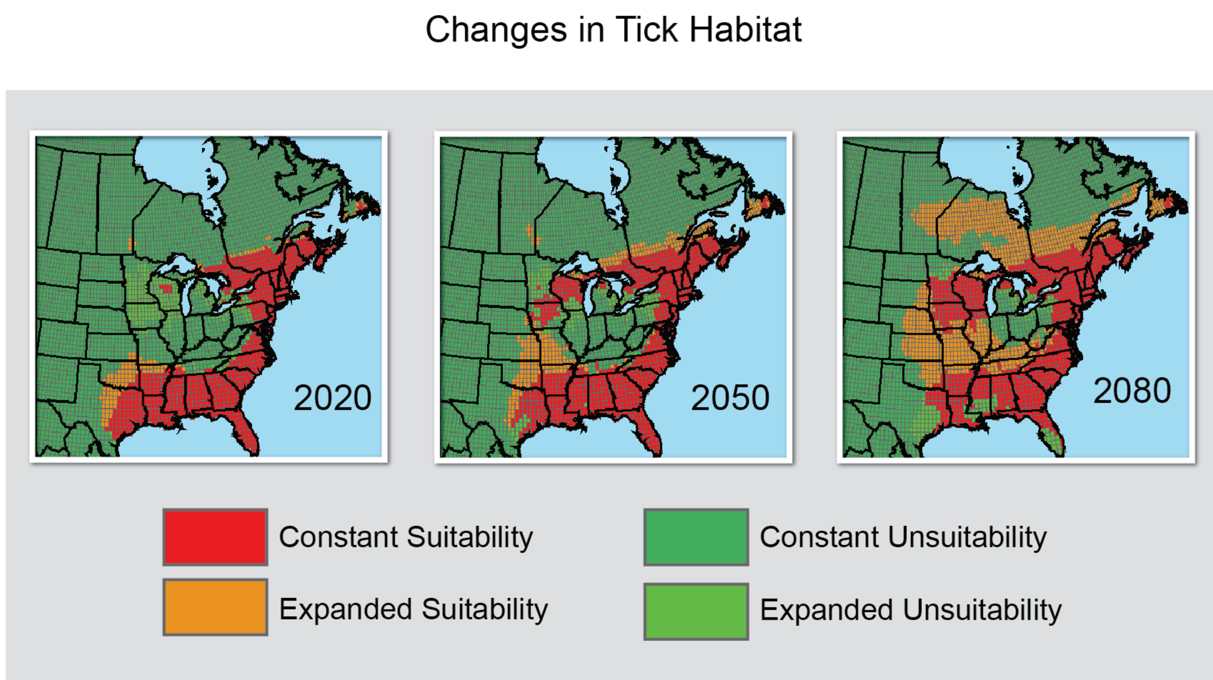

Figure 9.8: Changes in Tick Habitat

Caption: The maps show the projected change in suitable habitat for the tick that transmits Lyme disease for the 2020s, 2050s, and 2080s. The areas in orange are projected to be newly suitable habitat for the tick, with this expansion including Illinois, Kentucky, West Virginia, Tennessee, Arkansas, Missouri, Oklahoma, Kansas, and Nebraska by 2080. Parts of Florida, Mississippi, and Texas are projected to see a reduction in suitable habitat by 2080. (Ogden et al. 2008).

Food- and Waterborne Diarrheal Disease

Diarrheal disease is a major public health issue in developing countries and a persistent concern in the U.S. Exposure to a variety of pathogens in water and food causes diarrheal disease. Seasonality, air and water temperature, precipitation patterns, and extreme rainfall events are all known to affect disease transmission (Curriero et al. 2001; European Centre for Disease Prevention and Control 2012; Semenza et al. 2011). In the U.S., the elderly are most vulnerable to serious outcomes, and those exposed to inadequately or untreated groundwater will be among those most affected.

In general, diarrheal diseases including Salmonellosis and Campylobacteriosis are more common when temperatures are higher, (Fleury et al. 2006; Hall et al. 2011; Hu et al. 2007; Hu et al. 2010; Lipp et al. 2002; Naumova et al. 2007; Onozuka et al. 2010) though patterns differ by place and pathogen. Diarrheal diseases have also been found to occur more frequently in conjunction with both unusually high and low precipitation (Febriani et al. 2010; Nichols et al. 2009). Sporadic increases in streamflow rates, often preceded by rapid snowmelt (Harper et al. 2011) and changes in water treatment (Rizak and Hrudey 2008), have also been shown to precede outbreaks. Risks of waterborne illness and beach closures are expected to increase in the

Great Lakes region due to projected climate change (Patz et al. 2008; Perera et al. 2012).

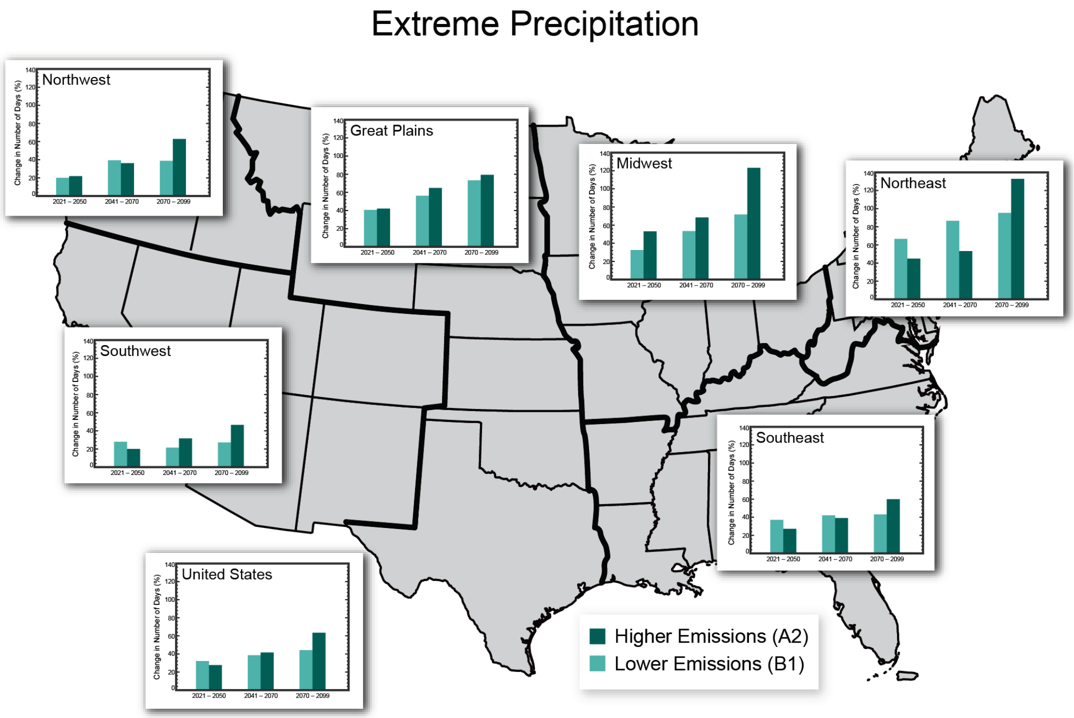

Figure 9.9: Extreme Precipitation

Caption: Projected increases in number of days per year with rainfall greater than 3 inches for 30-year averages centered on 2035, 2055, and 2085 (compared to 1971-2000) assuming a lower-emissions scenario in which emissions of heat-trapping gases are substantially reduced (B1, lighter blue bars on left) and a higher-emissions scenario in which emissions continue to grow (A2, darker bars on right). Waterborne disease outbreaks occur more frequently after extreme rainfall events, so more of these events will increase risks of associated illnesses. (Source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Statistically Downscaled.)

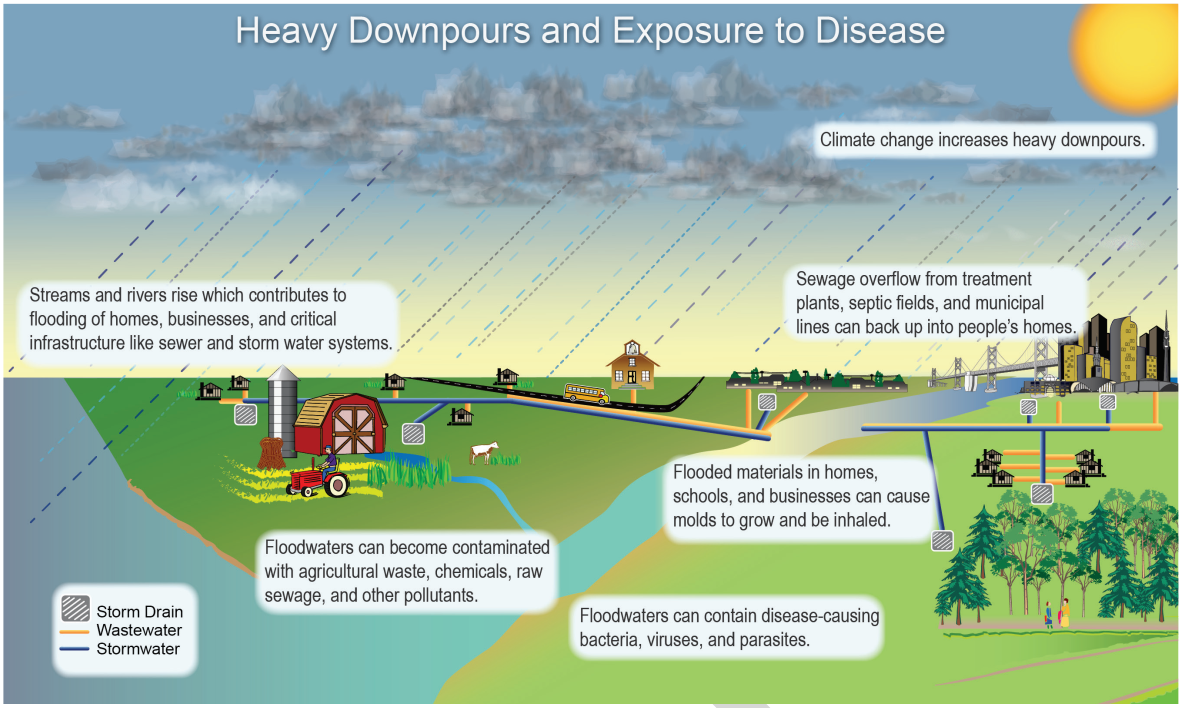

Figure 9.10: Heavy Downpours and Exposure to Disease

Caption: Heavy downpours, which are increasing in much of the U.S., have contributed to increases in heavy flood events (Ch. 2: Our Changing Climate, Key Message 6). The figure above illustrates how humans can become exposed to waterborne diseases, which typically present in the weeks following inundation (Teschke et al. 2010). Human exposures to waterborne diseases can occur via drinking water, as well as recreational waters. (Backer and Moore 2011; Backer et al. 2003; Backer et al. 2005; Backer et al. 2010; Glibert et al. 2005; Moore et al. 2008) (Figure source: NOAA NCDC / CICS-NC.)

Harmful Bloom of Algae

Figure 9.11: Harmful Bloom of Algae

Caption: Remote sensing color image of harmful algal bloom in Lake Erie. The bright green areas have high concentrations of algae, which can be harmful to human health. The frequency and range of harmful blooms of algae are increasing (Glibert et al. 2005; Moore et al. 2008). Because algae blooms are closely related to climate factors, projected changes in climate are likely affecting the observed changes in algae blooms. Other factors related to increases in harmful algal blooms include shifts in ocean conditions such as nutrient inputs (Backer and Moore 2011; Moore et al. 2008). (Source: NASA MODIS data provided by R. Stumpf, NOAA)

Food Security

Globally, climate change is expected to threaten both food production and certain aspects of food quality. Many crop yields are predicted to decline due to the combined effects of changes in rainfall, severe weather events, and increasing competition from weeds and pests on crop plants (Asseng et al. 2011; Battisti and Naylor 2009; Cohen et al. 2008; Gornall et al. 2010; Lobell et al. 2008; Schlenker and Roberts 2009; Schmidhuber and Tubiello 2007; Tubiello et al. 2007; Ziska et al. 2011; Ch. 6: Agriculture; Key Message 6). Livestock and fish production (Hoegh-Guldberg and Bruno 2010; Hoffmann 2010) is also projected to decline. Prices are expected to rise in response to declining food production and associated trends such as increasingly expensive petroleum (used for agricultural inputs such as such as pesticides and fertilizers) (Neff et al. 2011).

While the U.S. will be less affected than some other countries (Gregory et al. 2005; Lloyd et al. 2011), the nation will not be immune. Health can be affected in several ways. First, Americans with unique dietary patterns, such as Alaskan natives, will confront shortages of key foods (Brubaker et al. 2011). Second, food insecurity increases with rising food prices (Brown and Funk 2008; Hertel and Rosch 2010). In such situations, people cope by turning to nutrient-poor but calorie-rich foods, and/or they endure hunger, with consequences ranging from micronutrient malnutrition to obesity (Bloem et al. 2010). Third, the nutritional value of some foods is projected to decline. Elevated atmospheric CO_2 is associated with decreased nitrogen concentration, and therefore decreased protein, in many crops, such as barley, sorghum, and soy (Högy and Fangmeier 2008; Högy et al. 2009; Taub et al. 2008; Wieser et al. 2008). The nutrient content of crops is also projected to decline, with reduced levels of nutrients such as calcium, iron, zinc, vitamins, and sugars (Idso and Idso 2001). Fourth, farmers are expected to need to use more herbicides and pesticides because of increased growth of pests (Chakraborty and Newton 2011; Garrett et al. 2006; Gregory et al. 2009; Koleva and Schneider 2009) and weeds (Franks et al. 2007; McDonald et al. 2009) as well as with decreased effectiveness (Ziska and Teasdale 2000b) and duration (Bailey 2004) of some of these chemicals. Farmers, farmworkers, and consumers will thus sustain increased exposure to these substances and their residues, which can be toxic.

Mental Health and Stress-related Disorders

Mental illness is one of the major causes of suffering in the U.S., and extreme weather events can affect mental health in several ways (Berry et al. 2008; Berry et al. 2010; Doherty and Clayton 2011; Fritze et al. 2008; Reser and Swim 2011). First, mental health problems are common after disasters (Davidson and McFarlane 2006; Halpern and Tramontin 2007; Mills et al. 2007). For example, research demonstrated high levels of anxiety and post-traumatic stress disorder among people affected by Hurricane Katrina (Galea et al. 2007; Kessler et al. 2008), and similar observations have followed floods (Ahern et al. 2005; Fewtrell and Kay 2008), heat waves (Hansen et al. 2008), and wildfires (McFarlane and Van Hooff 2009) – events increasingly fueled by climate change (see Ch. 2: Our Changing Climate).

Second, some patients with mental illness are especially susceptible to heat (Bouchama et al. 2007; Bulbena et al. 2006). Suicide varies seasonally (Deisenhammer 2003) and rises with hot weather (Maes et al. 1994; Page et al. 2007), suggesting potential climate impacts on depression. Dementia is a risk factor for hospitalization and death during heat waves (Basu and Samet 2002; Hansen et al. 2008). Patients with severe mental illness such as schizophrenia are at risk during hot weather related both to their illness (Cusack et al. 2011; Shiloh et al. 2009; Shiloh et al. 2001) and to their medications (Martin-Latry et al. 2007; Stöllberger et al. 2009). Additional potential mental health impacts, less well understood, include the distress associated with environmental degradation (Albrecht et al. 2007; Higginbotham et al. 2006) and displacement (Loughry 2010; McMichael et al. 2010), and the anxiety and despair that knowledge of climate change might elicit in some people (Doherty and Clayton 2011).

Box: Multiple Climate Stressors and Health

Climate change impacts add to the *cumulative* stresses currently faced by vulnerable populations including children, the elderly, the poor, some communities of color, and people with chronic illnesses. These populations, and others living in certain places such as cities, floodplains, and coastlines, are more vulnerable not only to extreme events, but also to ongoing, persistent climate-related threats. These threats include poor air quality, heat, drought, flooding, and mental health stress. Over time, the accumulation of these stresses will be increasingly devastating to these populations.

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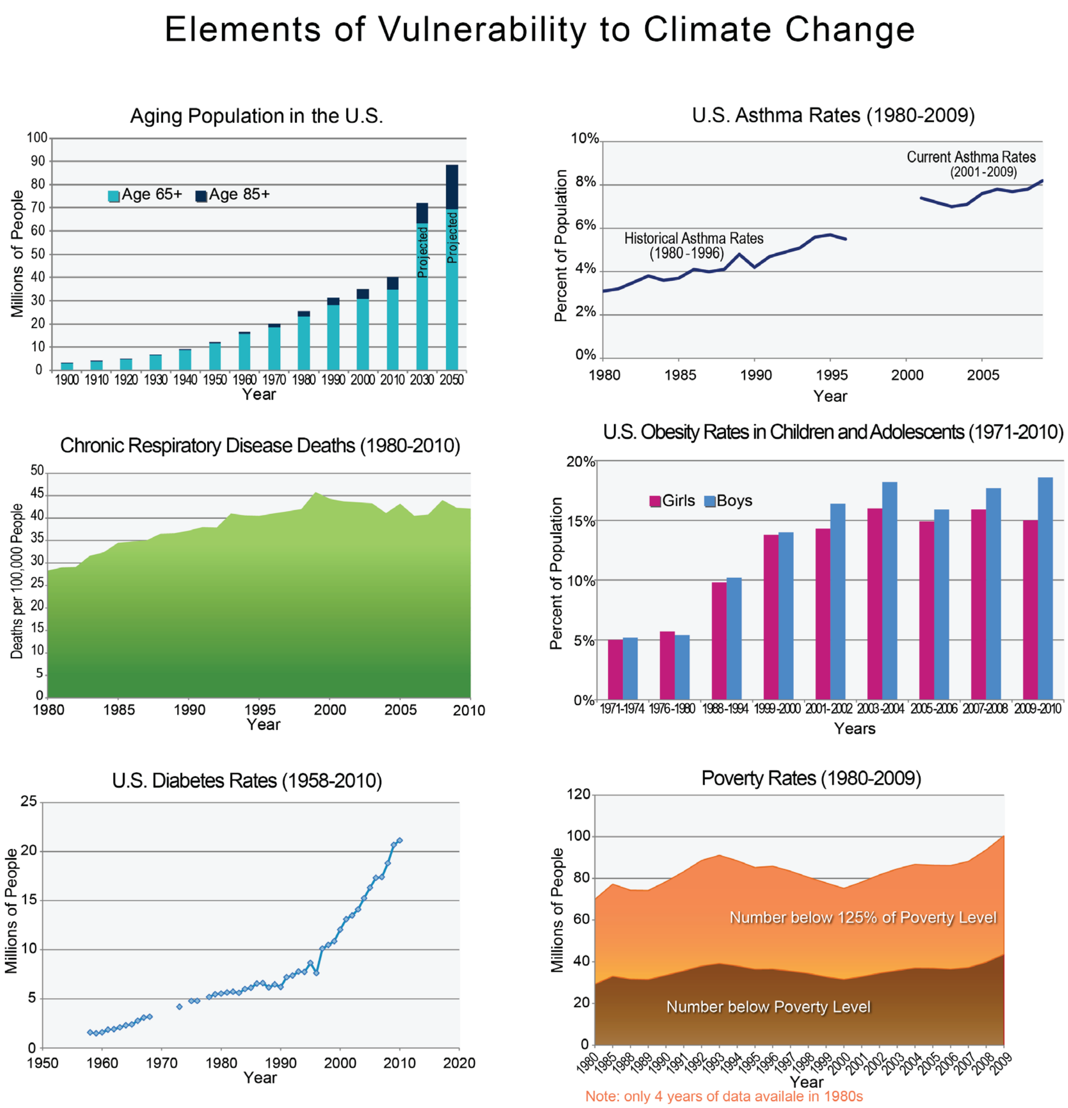

Figure 9.12: Elements of Vulnerability

Caption: A variety of factors can increase the vulnerability of a population to health effects due to climate change. For example, the elderly are more vulnerable to heat stress because their bodies are less able to regulate their temperature. U.S. population trends show rising numbers of elderly. Similarly, people who are obese and/or have diabetes, heart disease, or asthma are more vulnerable to a range of climate-related health impacts. Their numbers are also rising. The poor are less able to afford the kinds of measures that can protect them from various health impacts, so poverty is another increasing risk factor (CDC ; CDC ; Health E-Stat ; U.S. Census Bureau 2010, 2011).

Most Vulnerable at Most Risk

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Climate change will increase the risk of climate-related illness and death for a number of vulnerable subpopulations in the U.S. Children, primarily because of physiology and developmental factors, will disproportionately suffer from the effects of heat waves (Basu 2009), air pollution, infectious illness, and trauma resulting from extreme weather events (AAP 2007; Balbus and Malina 2009; Schmier and Ebi 2009; Sheffield and Landrigan 2011c; Sheffield et al. 2011b). The country's older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events (Balbus and Malina 2009; Basu 2009; Kovats and Hajat 2008; Zanobetti et al. 2012). Pre-existing health conditions also make the elderly susceptible to cardiac and respiratory impacts of air pollution (Reid et al. 2009) and to more severe consequences from infectious diseases (Chou et al. 2010); limited mobility among the elderly can also increase flood-related health risks (Brunkard et al. 2008). Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups (Basu 2009; Reid et al. 2009). Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population (Drewnowski 2009; Lloyd et al. 2011).

Box: Societal System Failures During Extreme Events

We have already seen *multiple system failures* during an extreme weather event in the U.S., as Hurricane Katrina ravaged New Orleans (Lister 2005). Infrastructure and evacuation failures and collapse of critical response services during a storm is one example. Another example is a loss of electrical power during a heat wave (Anderson and Bell 2012). Air conditioning has helped reduce illness and death due to extreme heat (Ostro et al. 2010), but if power is lost, everyone is vulnerable. By their nature, such events can exceed our capacity to respond (Hess et al. 2012). In succession, these events severely deplete our reserves from the personal to the national scale, but disproportionately affect the most vulnerable populations (Shonkoff et al. 2011).

Katrina Refugee Diaspora

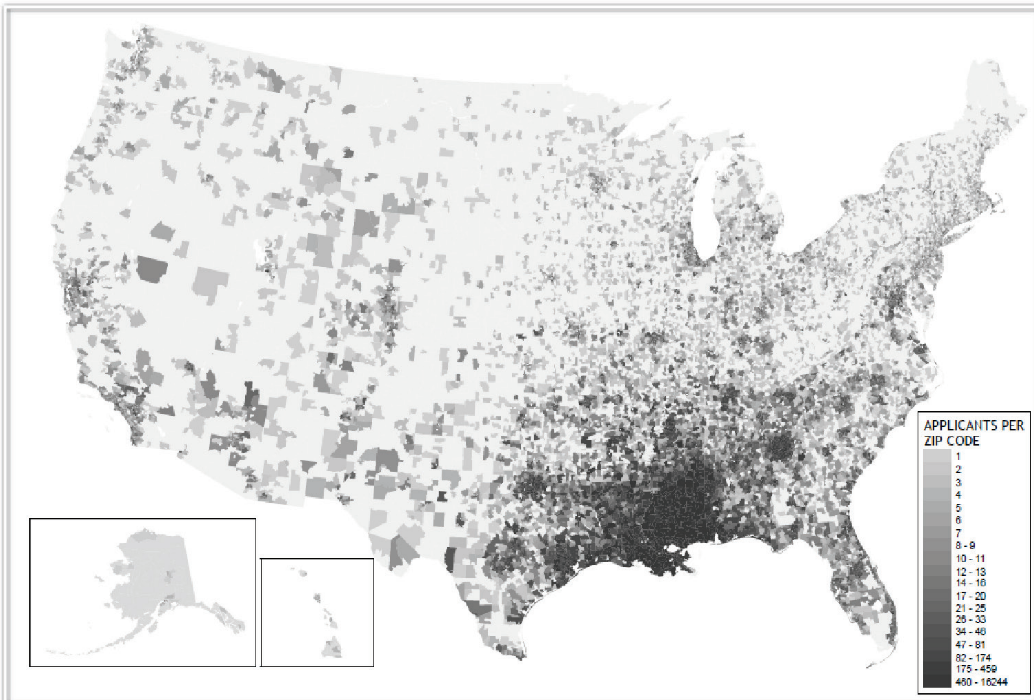

Figure 9.13: Katrina Refugee Diaspora

Caption: This map illustrates the national scope of the dispersion of refugees from Hurricane Katrina. It shows the location by zip code of the 800,000 displaced Louisiana residents who requested federal emergency assistance. The evacuees ended up dispersed across the entire nation, illustrating the wide-ranging impacts that can flow from extreme weather events, some of which are projected to increase in frequency and/or intensity as climate continues to change. (Source: Louisiana Geographic Information Center 2005)

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Climate change will disproportionately affect low-income communities (Balbus and Malina 2009; Bullard and Wright 2009b; Frumkin et al. 2008; Harlan et al. 2006; Martinez 2011; O'Neill and Ebi 2009; O'Neill et al. 2008; O'Neill et al. 2003, 2005; Pastor et al. 2006; Shonkoff et al. 2011), raising environmental justice concerns. Existing health disparities (Frumkin et al. 2008; Geronimus et al. 1996; Keppel 2007; National Heart Lung and Blood Institute Working Group 1995; Younger et al. 2008) and other inequities (Bullard et al. 2011; National Urban League 2009) increase vulnerability. For example, Hurricane Katrina demonstrated how vulnerable these populations were to extreme weather events, because many low-income and of-color New Orleans residents had difficulty evacuating and recovering from the storm (Bullard and Wright 2009b; Pastor et al. 2006). Other climate change related issues that have an equity component include heat waves and air quality (Bullard and Wright 2009b; Harlan et al. 2006; Martinez 2011; O'Neill et al. 2008; O'Neill et al. 2005; Shonkoff et al. 2011).

Prevention Provides Protection

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Prevention is a central tenet of public health. Many conditions that are difficult and costly to treat when a patient gets to the doctor could be prevented before they occur at a fraction of the cost. Similarly, many of the population health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur (Ebi et al. 2003; Frumkin et al. 2008). Early prevention, such as early warnings for extreme weather, can be particularly cost-effective (Chokshi and Farley 2012; Kosatsky 2005; Rhodes et al. 2010; The Community Preventitive Services Task Force 2012). As with many illnesses (Sherwood and Huber 2010), once impacts are apparent, even the best adaptive efforts can be overwhelmed, and damage control becomes the priority (IPCC 2012).

Box: Large-Scale Environmental Change Favors Disease Emergence
Climate change is causing large-scale changes in the environment, increasing the likelihood of the emergence or reemergence of unfamiliar disease threats (IOM 2008). Factors include shifting ranges of disease-carrying pests, lack of population immunity and preparedness, and inadequate disease monitoring. Diseases including Lyme disease and dengue fever pose increasing health threats to the U.S. population. The public health system is not currently prepared to monitor or respond to these growing disease risks. Introduction of a new disease, such as Chikungunya, has devastated populations in other countries around the world (Anyamba et al. 2012; Dwibedi et al. 2011; Rezza et al. 2007).

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The value of prevention is most apparent with activities that reduce carbon pollution, such as reliance on alternative energy sources for electricity production (Markandya et al. 2009) and more efficient and active transport such as biking or walking (Woodcock et al. 2009). Many such options have immediate public health benefits, such as lower rates of obesity, diabetes, and heart disease, and also reduce adverse climate-health impacts, producing cost savings in the near- and longer-term (Haines et al. 2009). The relationship holds for other types of prevention for exposures from climate change that are already apparent. For instance, heat wave early warning systems protect vulnerable populations very effectively, and are much less expensive than treating and coping with heat illnesses. Systems that monitor for early outbreaks of disease are also typically much less expensive than treating communities once outbreaks take hold.

Effective communication is a fundamental part of prevention. The public must understand risk in order to endorse proactive risk management. The public is familiar with the health risks of smoking, but not so for climate change. When asked about climate change, Americans don't mention health impacts, (Smith and Leiserowitz 2012) and when asked about health impacts specifically, most believe it will affect people in a different time or place (Leiserowitz 2005). But diverse groups of Americans find information on health impacts to be helpful once received, particularly information about the health benefits of mitigation (reducing carbon emissions) and adaptation (Maibach et al. 2010).

Determining which types of prevention to invest in (such as monitoring, early warning systems, and land-use changes that reduce the impact of heat and floods) depends on several factors, including health problems common to that particular area, vulnerable populations, the preventive health systems already in place, and the expected impacts of climate change (Ebi et al. 2006). Local capacity to adapt is very important; unfortunately the most vulnerable populations also frequently have limited resources for managing climate-health risks.

Overall, the capacity of the American public health and health care delivery systems is decreasing: health insurance coverage has been declining (DeNavas-Walt et al. 2011), the number of hospital emergency departments is dropping (Hsia et al. 2011), and funding for public health programming is increasingly limited. The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable, especially with shortages of health care and public health professionals projected by 2020 (Derksen and Whelan 2009; Johnson 2008) . Without careful consideration of how to prevent future impacts, similar patterns could emerge regarding the health impacts from climate change.

There are public health programs in some locations that address climate-sensitive health issues, and integrating such programs into the mainstream as adaptation needs increase would improve public health resilience to climate change (Ebi et al. 2009). Given that these programs have demonstrated efficacy against current threats that are expected to worsen, it is prudent to expand investment in these programs now (Frumkin et al. 2008). Climate change preparedness activities and climate-health research are significantly underfunded (Ebi et al. 2006), but there is an opportunity to address this shortfall before needs become more widespread.

Responses Have Multiple Benefits

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Policies and other strategies intended to reduce carbon pollution and mitigate climate change can often have independent influences on human health. For example, reducing CO_2 emissions through renewable electrical power generation can reduce air pollutants like particles and sulfur dioxide. Efforts to improve the resiliency of communities and human infrastructure to climate change impacts can also affect human health. Some of these efforts will benefit health, but some could potentially be harmful. There is a growing recognition that the magnitude of these health "co-benefits" or "co-harms" could be significant, both from a public health and an economic standpoint (Haines et al. 2009).

Much of the focus of health co-benefits has been on reducing health-harming air pollution (Bell et al. 2008; Markandya et al. 2009; Nemet et al. 2010; Shindell et al. 2011; Wilkinson et al. 2009; Woodcock et al. 2009). One study projects that eliminating short motor vehicle trips in 11 Midwestern metropolitan areas, and instead replacing 50% of those motor vehicle trips with bicycle use, would avoid nearly 1,300 deaths and create up to $8 billion dollars in health benefits annually for the upper Midwest region (Grabow et al. 2012). Such multiple-benefit actions can reduce heat-trapping gas emissions that lead to climate change, improve air quality by reducing vehicle pollutant emissions, and improve fitness and health through increased physical activity (Bambrick et al. 2011; Kjellstrom and Weaver 2009; Parker 2011; Patz et al. 2008).

Innovative urban design could create increased access to active transport (Patz et al. 2008). The compact geographical area found in cities presents opportunities to reduce energy use and emissions of heat-trapping gases and other air pollutants through active transit, improved building construction, provision of services, and infrastructure creation, such as bike paths and sidewalks (Bambrick et al. 2011; Wilkinson et al. 2007). Urban planning and design could produce additional societal co-benefits by promoting social interaction and prioritizing vulnerable urban populations (Bambrick et al. 2011).

Strategies to reduce heat-trapping gas emissions can also produce immediate health benefits through means other than air pollution reductions. One example is a reduction in red meat consumption. Emissions of methane from livestock production account for 20% of the U.S. total (McMichael et al. 2007; Parker 2011). While there are several means to reduce methane emissions, a reduction achieved through an overall decrease in the consumption, and therefore production, of red meat could have near-term health benefits (Parker 2011) that include a reduction in cardiovascular disease and the occurrence of some cancers (Friel 2010; Friel et al. 2009).

Climate change mitigation and adaptation policy could also reduce health-related disparities between wealthy and poor communities, yielding positive equity impacts (Luber and Prudent 2009). Several studies have found that communities of color and poor communities experience disproportionately high exposures to air pollution (Ash et al. 2009; Pastor et al. 2004; Pellizzari et al. 1999; Perlin et al. 1995; Wernette and Nieves 1992). Climate change mitigation policies that improve local air quality thus have the potential to strongly benefit health in these communities.

An area where adaptation policy could produce more equitable health outcomes is with respect to extreme weather events. As discussed earlier, Hurricane Katrina demonstrated that communities of color, poor communities, and certain other identifiable populations (like new immigrant communities) are more vulnerable to the adverse effects of extreme weather events (Pastor et al. 2009). These vulnerable populations could benefit from urban planning policies that ensure that new buildings, including homes, are constructed to resist extreme weather events (Bambrick et al. 2011).

Policies to reduce climate change also have the potential to improve the food security of low-income residents by preventing decreased crop production due to climate change, thereby avoiding associated increases in food prices.

Traceable Accounts

Chapter 9: Human Health

Key Message Process: The key messages were developed during technical discussions and expert deliberation at a two-day meeting of the eight chapter Lead Authors, plus Susan Hassol and Daniel Glick, held in Boulder, Colorado May 8-9, 2012; through multiple technical discussions via six teleconferences from January through June, 2012, and an author team call to finalize the Traceable Account draft language on Oct 12, 2012; and through other various communications on points of detail and issues of expert judgment in the interim. The author team also engaged in targeted consultations during multiple exchanges with Contributing Authors, who provided additional expertise on subsets of the key message. These discussions were held after a review of the technical inputs and associated literature pertaining to Human Health, including a literature review (Balbus and Malina 2009), workshop reports for the northwestern and Southeastern U.S. and additional technical inputs on a variety of topics.

Key message #1/4	**Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, diseases transmitted by insects, food and water, and threats to mental health. Some of these health impacts are already underway in the U.S.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review (Balbus and Malina 2009) and workshop reports for the NW and SE U.S. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input. **Air Pollution:** The effects of decreased air quality on human health have been well documented concerning projected increases in ozone (Bell et al. 2008; Bell et al. 2007; Chang et al. 2010; Ebi and Semenza 2008; Jacob and Winner 2009; Kjellstrom et al. 2010; Liao et al. 2009; Spickett et al. 2011; Tagaris et al. 2007), which leads to a number of health impacts (Dennekamp and Carey 2010; Kampa and Castanas 2008; Kinney 2008). **Allergens:** The effects of increased temperatures and atmospheric CO_2 concentration has been documented with studies showing that reduced health will result from increased exposure to aeroallergens (Ariano et al. 2010; Breton et al. 2006; D'amato and Cecchi 2008; Emberlin et al. 2002; Pinkerton et al. 2012; Reid and Gamble 2009; Schmier and Ebi 2009; Shea et al. 2008; Sheffield and Landrigan 2011c; Sheffield et al. 2011a; Staudt et al. 2010; Ziska 2011) **Wildfire:** The effects of wildfire on human health have been well documented with the increase in frequency (Jacob and Winner 2009; Littell et al. 2009; MacDonald 2010; Mills 2009; Shea et al. 2008; Westerling and Bryant 2008; Westerling et al. 2006; Westerling et al. 2011) leading to decreased air quality (Akagi et al. 2011; Dennekamp and Abramson 2011; Jaffe et al. 2008a; Jaffe et al. 2008b; Pfister et al. 2008; Spracklen et al. 2007) and negative health impacts (Delfino et al. 2009; Dennekamp and Abramson 2011; Jenkins et al. 2009; Lee et al. 2009). **Temperature Extremes:** The effects of temperature extremes on human health have been well documented for increased heat waves (Duffy and Tebaldi 2012; Hayhoe et al. 2010; IPCC 2007; Jackson et al. 2010), which cause more deaths (Basu 2009; Rey et al. 2007), hospital admissions (Lin et al. 2009; Nitschke et al. 2011; Ostro et al. 2009) and population

vulnerability (Johnson et al. 2009; Wilby 2008)

Extreme Weather Events:
The effects of weather extremes on human health have been well documented, particularly for increased heavy precipitation, which leads to more deaths (Ashley and Ashley 2008; NOAA 2010), waterborne diseases (Teschke et al. 2010), and illness (Mendell et al. 2011).

Diseases from Insects and Rodents:
The effects of climate change on diseases transmitted by insect and rodents (vector-borne and zoonotic diseases) have been documented in a number of publications. Studies have explored the effects climate change have on location and adaptation of insects (Lafferty 2009; McGregor 2011; Tabachnick 2010), which can alter their interaction and effect with human health (Epstein 2010; Reiter 2008; Rosenthal 2009; Russell 2009), and have documented a number of insect-borne diseases affect the U.S. (Centers for Disease Control and Prevention 2010; Degallier et al. 2010; Diuk-Wasser et al. 2010; Gong et al. 2011; Johansson et al. 2009; Jury 2008; Keesing et al. 2009; Kolivras 2010; Lambrechts et al. 2011; Mills et al. 2010; Morin and Comrie 2010; Ogden et al. 2008; Ramos et al. 2008). Observational studies are already underway and confidence is high based on scientific literature that climate change has contributed to the expanded range of certain disease vectors, including *Ixodes* ticks which are vectors for Lyme disease in the U.S.

Food- and Waterborne Disease:
There has been extensive research concerning the climate change effects on water- and food-borne disease transmission (Febriani et al. 2010; Fleury et al. 2006; Harper et al. 2011; Hu et al. 2007; Hu et al. 2010; Lipp et al. 2002; Naumova et al. 2007; Nichols et al. 2009; Onozuka et al. 2010; Rizak and Hrudey 2008; Semenza et al. 2011). The current evidence base strongly supports that waterborne diarrheal disease is both seasonal and sensitive to climate variability. There are also multiple studies associating extreme precipitation events with waterborne disease outbreaks (Curriero et al. 2001). This evidence of responsiveness to weather and climate, combined with evidence strongly suggesting that temperatures will increase and extreme precipitation events will increase in frequency and severity, provides a strong argument for climate change impacts on waterborne disease by analogy. There are multiple studies associating extreme precipitation events with waterborne disease outbreaks, and strong climatologic evidence for increasing frequency and intensity of extreme precipitation events in the future. The scientific literature modeling projected impacts of climate change on waterborne disease is somewhat limited, however. Combined, we therefore have overall medium confidence in the impact of climate change on waterborne disease.

Harmful Algal Blooms:
The effects of biogenic systems on human health has been extensively studied with showing that reduced health will result from increased spread and frequency of harmful algae blooms (Backer and Moore 2011; Glibert et al. 2005; Moore et al. 2008), which have multiple exposure routes (Backer et al. 2003; Backer et al. 2005; Backer et al. 2010). Additional studies have shown extreme rainfall and higher temperatures leads to higher fungi and mold health concerns (Fisk et al. 2007; IOM 2011; Mudarri and Fisk 2007; Wolf et al. 2010).

Food Security:
Climate change is expected to have global impacts on both food production and certain aspects of food quality. The impact of temperature extremes, changes in precipitation and elevated atmospheric CO2, and increasing competition from weeds and pests on crop plants is an area of active research (Asseng et al. 2011; Battisti and

	Naylor 2009; Cohen et al. 2008; Gornall et al. 2010; Lobell et al. 2008; Schlenker and Roberts 2009; Schmidhuber and Tubiello 2007; Tubiello et al. 2007; Ziska et al. 2011; Ch. 6: Agriculture; Key Message on Food Security). While the U.S. as a whole will be less affected than some other countries, the most vulnerable, including those dependent on subsistence lifestyles, especially as Alaskan natives, will not be immune. **Threats to Mental Health:** The effects of climate change on mental health have been extensively studied (Berry et al. 2008; Doherty and Clayton 2011; Fritze et al. 2008; Reser and Swim 2011). Studies have shown the impacts of mental health problems caused after disasters (Davidson and McFarlane 2006; Halpern and Tramontin 2007; Mills et al. 2007), with extreme events like Hurricane Katrina (Galea et al. 2007; Kessler et al. 2008), floods (Ahern et al. 2005; Fewtrell and Kay 2008), heat waves (Hansen et al. 2008), and wildfires (McFarlane and Van Hooff 2009) have lead to mental health problems. Further work has shown that people with mental illnesses are increasingly vulnerable under heat waves, which are linked to suicide (Deisenhammer 2003; Maes et al. 1994; Page et al. 2007), increased hospitalization and death for dementia patients (Basu and Samet 2002; Hansen et al. 2008) , increased risk for schizophrenia patients (Cusack et al. 2011; Martin-Latry et al. 2007; Shiloh et al. 2009; Shiloh et al. 2001; Stöllberger et al. 2009), and a number of other mental illnesses (Albrecht et al. 2007; Doherty and Clayton 2011; Fritze et al. 2008; Higginbotham et al. 2006; Loughry 2010; McMichael et al. 2010).
New information and remaining uncertainties	Important new evidence on heat-health effects (Åström et al. 2011; Ye et al. 2012; Zanobetti et al. 2012) confirmed many of the findings from a prior literature review. Uncertainties in the magnitude of projections of future climate-related morbidity and mortality can result from differences in climate model projections of the frequency and intensity of extreme weather events such as heat-waves and other climate parameters such as precipitation. Efforts to improve the information base should address the coordinated monitoring of climate and improved surveillance of health effects.
Assessment of confidence based on evidence	Overall: **Very High** confidence. There is considerable consensus and a high quality of evidence in the published peer-reviewed literature that a wide range of health effects will be exacerbated by climate change in the U.S. There is less agreement on the magnitude of these effects, because of the exposures in question; and the multi-factorial nature of climate-health vulnerability, with regional and local differences in underlying health susceptibilities and adaptive capacity. Other uncertainties include how much effort and resources will be put into improving the adaptive capacity of public health systems to prepare in advance for the health effects of climate change, and prevent the degree of harm to individual and community health, and limit associated health burdens and societal costs. Decreased Air Quality: **Very High** confidence. Allergens: **High** confidence. Wildfires: **Very High** confidence. Thermal Extremes: **Very High** confidence. Extreme Weather Events: **Very High** confidence. Vector-borne Infectious Diseases: **High** confidence. Food- and Waterborne disease: **Medium** confidence. Harmful Algal Blooms: **Medium** confidence. Food Security: **Medium** confidence for food quality; **High** confidence for food

	security. Threats to Mental Health: **Very high** confidence for post-disaster impacts; **Medium** confidence for climate-induced stress.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 9: Human Health

Key Message Process: See process for Key Message #1

Key message #2/4	**Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review (Balbus and Malina 2009) (Balbus, 2012) and workshop reports for the NW and SE U.S. (Schramm, 2012) Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input. **Amplification of existing health threats**: The effects of extreme heat and heat waves; worsening air pollution and asthma; extreme rainfall and flooding and displacement;, and injuries associated with extreme weather events, fueled by climate change, are already substantial public health issues. Trends projected under a changing climate are likely to exacerbate these health effects in the future (IPCC SREX 2012). **Children**: The effects of climate change increase vulnerability of children to extreme heat, and increased health damage (morbidity, mortality) resulting from heat waves has been well documented (Duffy and Tebaldi 2012; Hayhoe et al. 2010; Jackson et al. 2010; Schmier and Ebi 2009; Shea 2007; Sheffield et al. 2011a). Extreme heat also causes more pediatric deaths (Basu 2009; Rey et al. 2007), more emergency room visits and hospital admissions (Knowlton et al. 2009; Lin et al. 2009; Nitschke et al. 2011; Ostro et al. 2009). More adverse effects from increased heavy precipitation can lead to more pediatric deaths, waterborne diseases (Teschke et al. 2010), and illness (Mendell 2007). **The elderly:** Heat stress is especially damaging to the health of older people (Balbus and Malina 2009; Basu and Samet 2002; Knowlton et al. 2009; Kovats and Hajat 2008; Medina-Ramón and Schwartz 2007; Zanobetti et al. 2012); as are climate-sensitive increases in air pollution (Centers for Disease Control and Prevention 2010). **The sick:** People and communities lacking the resources to adapt, to enhance mobility and escape health-sensitive situations, are at relatively high risk (Harlan et al. 2006). Climate change will disproportionately impact low-income communities and some communities of color, raising environmental justice concern (Balbus and Malina 2009; Frumkin et al. 2008; Geronimus et al. 1996; Harlan et al. 2006; Keppel 2007; National Heart Lung and Blood Institute Working Group 1995; O'Neill et al. 2008; O'Neill et al. 2003; O'Neill et al. 2005; Pastor et al. 2006; Shonkoff et al. 2011; Uejio et al. 2011 (Bullard and Wright 2009a) Existing health disparities {Frumkin, 2008 #6444; Younger et al. 2008) and other inequities (Bullard et al. 2011; National Urban League 2009) increase vulnerability. For example, Hurricane Katrina demonstrated how vulnerable these populations were to extreme weather events because many low-income and of-color New Orleans residents had difficulty evacuating and recovering from the storm (Bullard and Wright 2009b; Pastor et al. 2006). Other climate change-related issues that have an equity component include heat waves and air quality (Balbus and Malina 2009; Harlan et al. 2006; O'Neill et al. 2008; O'Neill et al. 2003; O'Neill et al. 2005;

	Shonkoff et al. 2011). **The poor:** People and communities lacking the resources to adapt, to enhance mobility and escape health-sensitive situations, are at relatively high risk (Harlan et al. 2006). Climate change will disproportionately impact low-income communities and some communities of color, raising environmental justice concern (Balbus and Malina 2009; Bullard et al. 2011; Frumkin 2002; Harlan et al. 2006; O'Neill et al. 2008; O'Neill et al. 2003; O'Neill et al. 2005; Pastor et al. 2006; Shonkoff et al. 2011; Uejio et al. 2011; White-Newsome et al. 2009). Existing health disparities (Frumkin et al. 2008; Geronimus et al. 1996; Keppel 2007; National Heart Lung and Blood Institute Working Group 1995; Younger et al. 2008) and other inequities (Bullard et al. 2011; National Urban League 2009) increase vulnerability. For example, Hurricane Katrina demonstrated how vulnerable these populations were to extreme weather events because many low-income and of-color New Orleans residents had difficulty evacuating and recovering from the storm (Bullard and Wright 2009b; Pastor et al. 2006) . Other climate change-related issues that have an equity component include heat waves and air quality (Balbus and Malina 2009; Harlan et al. 2006; O'Neill et al. 2008; O'Neill et al. 2003; O'Neill et al. 2005; Shonkoff et al. 2011). **Some communities of color:** There are racial disparities in climate-sensitive exposures to extreme heat in urban areas, and in access to means of adaptation i.e. air conditioning use (O'Neill et al. 2005; Shonkoff et al. 2011; Uejio et al. 2011; White-Newsome et al. 2009). There are also racial disparities in withstanding, and recovering from, extreme weather events (Bullard and Wright 2009b; Pastor et al. 2006). Current epidemiological evidence on the climate-sensitive health outcomes in the U.S. indicate that health impacts will differ substantially by location, pathway of exposure, underlying susceptibility and adaptive capacity. These disparities in health impacts will largely result from differences in the distribution of individual attributes in a population that confer vulnerability (age, socioeconomic status, race) as well as attributes of place that modulate or amplify exposure (flood-plain, coastal zone, urban heat island), as well as the resilience of critical public health infrastructure.
New information and remaining uncertainties	Important new evidence (Zanobetti et al. 2012) confirmed findings from a prior literature review. Due to uncertainties in rates of adaptation, and implementation of public health interventions that aim to address underlying health disparities and determinants of health, the potential for specific climate-vulnerable communities to experience highly harmful health effects is not entirely clear in specific regions and on specific time frames (Luber and Prudent 2009). We haven't yet had frequent opportunities as a public health community to evaluate the overall success and successful elements of adaptation interventions.
Assessment of confidence based on evidence	Will amplify existing health threats: **Very high**. Among those especially vulnerable are: Children: **Very high**. The elderly: **Very high**. The sick: **Very high**.

	The poor: **Very high**. Some communities of color: **High**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 9: Human Health

Key Message Process: See process for Key Message #1

Key message #3/4	**Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review (Balbus and Malina 2009) and workshop reports for the NW and SE U.S. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input. A number of studies have demonstrated prevention activities, like using alternative energy sources (Markandya et al. 2009) and using active transportation like biking or walking (Grabow et al. 2012; Woodcock et al. 2009), can lead to significant public health benefits, which can save costs in the near and long term (Haines et al. 2009). For example, a study performed by Ebi et al. (Ebi et al. 2003) reports that heat wave early warning systems are cheaper than treating heat related illnesses. There are also publications on existing programs that have improved public health resilience (Ebi and Semenza 2008; Frumkin et al. 2008). However, studies have shown that factors such as determining what type of prevention to invest in (Ebi et al. 2006), underfunding of climate-health research and preparedness activities (Ebi et al. 2009), and the declining health care system (DeNavas-Walt et al. 2011; Hsia et al. 2011) will inhibit our prevention potential. The cost-effectiveness of many prevention activities is well established (Derksen and Whelan 2009). Some preventive actions are cost saving, while others are deemed cost-effective based on a pre-determined threshold, and overall a larger proportion of effective prevention efforts are cost-saving compared with clinical interventions that address disease once symptoms are manifest (Chokshi and Farley 2012). There is less information on the cost-effectiveness of specific prevention interventions relevant to climate sensitive health threats (e.g. heat early warning systems), however. Overall, we thus have high confidence for this portion of the message. The inverse relationship between the magnitude of an impact and a community's ability to adapt is well established and understood. Two extreme events, Hurricane Katrina and the European wave of 2003, illustrate this relationship well (Kosatsky 2005; Rhodes et al. 2010). Extreme events interact with social vulnerability to produce extreme impacts, and the increasing frequency of extreme events associated with climate change is prompting concern for impacts that may overwhelm adaptive capacity (IPCC 2012; Rezza et al. 2007). This is equally true of the public health sector, specifically, leading to very high confidence in this statement.
New information and remaining uncertainties	A key issue (uncertainty) is the extent to which the nation, states, communities and individuals will be able to adapt to climate change, because this depends on the levels of local exposure to climate-health threats, underlying susceptibility, and the capacities to adapt that are available at each scale. Currently the capacity of the American public health and health care delivery systems are decreasing, making the U.S. population even more vulnerable (Derksen and Whelan 2009; Johnson et al. 2009). Steps for improving the information base on adaptation include undertaking a more comprehensive evaluation of existing climate-health preparedness programs and

	their effectiveness in various jurisdictions (cities, counties, states, nationally).
Assessment of confidence based on evidence	Overall: **High**. **High**: Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Prevention provides the most protection; but we do not as yet have a lot of evaluation information from preparedness plans post-implementation. **High**: Early action provides the largest health benefits. There is evidence that heat-health early warning systems have saved lives and money in U.S. cities like Philadelphia, PA (Ebi et al. 2003). **Very high**: Our ability to adapt to future changes may be limited.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 9: Human Health

Key Message Process: See process for Key Message #1

Key message #4/4	**Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review (Balbus and Malina 2009) and workshop reports for the NW and SE U.S. (Schramm, 2012) Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input. A number of studies have explored the opportunities available to improve health and well-being as a result of adapting to climate change (Haines et al. 2009), with many recent publications illustrating the benefit of reduced air pollution (Bell et al. 2008; Markandya et al. 2009; Nemet et al. 2010; Shindell et al. 2011; Smith and Haigler 2008; Wilkinson et al. 2009; Woodcock et al. 2009). Additionally, some studies have looked at the co-benefits to climate change and health by applying innovative urban design practices which includes to reduce energy consumption and pollution while increasing public health (Bambrick et al. 2011; Grabow et al. 2012; Kjellstrom and Weaver 2009; Patz et al. 2008), and decreased vulnerability of communities to extreme events (Bambrick et al. 2011; Pastor et al. 2009) and the disparity between different societal groups (Ash et al. 2009; Luber and Prudent 2009; Pastor et al. 2004; Pellizzari et al. 1999; Perlin et al. 1995; Wernette and Nieves 1992). Even something as simple as eating less red meat has been reported to combat climate change (Kjellstrom and Weaver 2009; McMichael et al. 2007; Parker 2011) and improve health (Friel 2010; Friel et al. 2009; Parker 2011).
New information and remaining uncertainties	More studies are needed to fully evaluate both the intended and unintended health consequences of efforts to improve the resiliency of communities and human infrastructure to climate change impacts. There is a growing recognition that the magnitude of these health co-benefits or co-harms could be significant, both from a public health and an economic standpoint.
Assessment of confidence based on evidence	**Very high**

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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10. Water, Energy, and Land Use

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Key Messages

1. **Energy, land, and water systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate vulnerability as well as adaptation and mitigation options for different regions of the country.**
2. **The dependence of energy systems on land availability and water supplies will influence their development and constrain some options for reducing greenhouse gas emissions.**
3. **Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is difficult, but can improve the analysis of options for reducing climate change impacts.**

Energy, water and land systems interact in many ways. Energy projects – coal-fired power, biofuel, solar farms – require varying amounts of water and land; water projects – water supply, irrigation – require energy and land; and land activities – agriculture, forestry – depend upon energy and water. Increasing population and a growing economy intensify these interactions (Skaggs et al. 2012). Climate change impacts each of these sectors directly, and because of the many connections between them, sectoral responses are often intensified or offset.

The implications of climate change for the energy, land, and water sectors have been studied extensively (see Ch. 4: Energy, Ch. 13: Land Use and Land Cover Changes, and Ch. 3: Water Resources of this report). Bilateral relationships between energy and water, land and water, and energy and land have also received significant attention. There are few analyses, however, on how the competition for multiple resources such as water supply, land availability, or environmental considerations (for example, biodiversity) interacts with decision-making for future energy demand and production in a changing climate.

Recent events such as the drought and heat waves experienced across much of the U.S. during the summers of 2011 and 2012 do provide some insights. They demonstrated that weather impacts within each of these sectors create cascading interactions among energy, land, and water sectors. High temperatures caused increased demand for electricity for air conditioning, which corresponded to increased water withdrawal and consumption for electricity generation. Heat, increased evaporation, drier soils, and lack of rain led to higher irrigation demands, which added stress on water resources required for energy production. At the same time, low-flowing and warmer rivers resulted in temporarily suspended power plant production in several states due to environmental concerns, reducing the options for dealing with the concurrent increase in electricity demand.

Challenges from climate change will arise from longer-term, more gradual change, as well as from projected changes in weather extremes. Energy production already competes for water resources with agriculture, human consumption, and natural systems. It is projected that climate-driven changes in land cover and land use will further affect water quality and availability. In turn, diminishing water quality and availability requires more energy to purify water and more infrastructure on land to store and distribute water.

The availability of energy, water, and land resources and the ways in which they interact vary across U.S. regions. U.S. regions differ in their: a) energy mix (solar, wind, coal, hydropower); b) precipitation and temperature patterns; c) sources and quality of available water resources (for example, ground, surface, recycled); d) technologies for storing, transporting, and using water; and e) land use and land cover (see Ch. 13: Land Use and Land Cover Changes). Because of these unique regional characteristics, impacts and related risks and vulnerabilities to climate change vary widely. Mitigation and adaptation options also differ significantly across regions.

Interactions among water, energy, and land resources are influencing and will influence technologies deployed in the future energy system. Energy technologies vary widely in their demands for land and water. Current competition for water supplies is leading to deployment of more expensive, but less water-intensive technologies, such as dry cooling for thermoelectric generation and photovoltaics for solar energy production. Competition for land and water resources is expected to intensify and will further affect technology choices in the future.

In some situations, land and water constraints limit options for reducing greenhouse gas emissions aimed at mitigating future climate change. For example, rapidly growing energy options such as solar power, biofuels, or expanded use of natural gas reduce net greenhouse gas emissions. In addition, these fuels reduce U.S. dependence on foreign energy resources and, at least in the case of shale gas, provide greater geographic diversity and resilience in supply, reducing dependence on supplies from the Gulf of Mexico. But, as with other technologies, these energy sources utilize land and water resources and are often not consistent with existing management strategies. For example, utility-scale concentrated solar power plants require relatively large tracts of land, and early siting efforts have raised environmental concerns.

Current challenges in siting land- and water-intensive energy facilities are likely to intensify over time as competition for these resources grows. With most of the potential deployment of concentrating solar technologies in the Southwest, facilities will need to be extremely water-efficient in order to compete for limited water resources. Raising crops to produce biofuels uses arable land and water that might otherwise be available for food production. This fact came into stark focus during the summer of 2012 when drought caused poor corn harvests, raising concerns about allocation of the harvest for food versus ethanol. Natural gas production from shale formation presents similar resource challenges. Technology breakthroughs in hydraulic fracturing have made shale gas production economical and dramatically changed the U.S. gas supply and price outlook, potentially for decades. At current prices, natural gas is replacing coal-fired electric generation, and the U.S. Energy Information Administration (EIA) projects that natural gas will continue on this trajectory. The observed decline in U.S. carbon emissions in 2011 has been directly attributed to increased penetration of natural gas into the U.S. energy portfolio, among other factors (EIA 2012). However, shale gas production requires significant amounts of water at the local scale, which creates demands on regional water resources. Water quality issues have also been raised and are the subject of ongoing research. Competition for land and water in a changing climate influences technology choices and subsequently limits some technologies that could be positive contributors to mitigating greenhouse gas emissions. These kinds of tradeoffs – mitigation strategies to reduce greenhouse gasses versus land and water resources required to implement mitigation technologies – will need to be jointly considered.

Conflicting stakeholder perceptions, institutional commitments, and international concerns can limit options for reducing vulnerability to climate change, and interactions among water, energy, and land resource sectors have the potential to intensify such constraints. Resource management decisions are often focused on just one of these sectors. Where the three sectors are tightly coupled, options for mitigating or adapting to climate change and consideration of the tradeoffs associated with technological or resource availability may be limited. For example, the Columbia River Treaty between Canada and the U.S. emphasizes hydroelectric power and flood control (see Columbia River section below).

Cascading Events

Energy, land, and water systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate vulnerability as well as adaptation and mitigation options for different regions of the country.

Energy production, land use, and water resources are linked in increasingly complex ways. Electric utilities and energy companies compete with farmers and ranchers for water rights in many parts of the country. Land use planners must consider the impacts of strained water supplies on cities, agriculture, and ecological needs. Across the country, these intertwined sectors will witness increased stresses due to climate changes that are projected to lower water quality and/or quantity in many regions and increase heat-related electricity demand, among other impacts.

In 2011, drought spread across the south-central U.S., causing a series of energy, water, and land impacts that demonstrate the connections among these sectors. Texans, for example, experienced the hottest and driest summer on record. Summer average temperatures were 5.2°F higher than normal, and precipitation was lower than previous records set in 1956. The associated heat wave, with temperatures above 100°F for 40 consecutive days, together with drought, strained the region's energy and water resources (Hoerling et al. 2012; NCDC 2012).

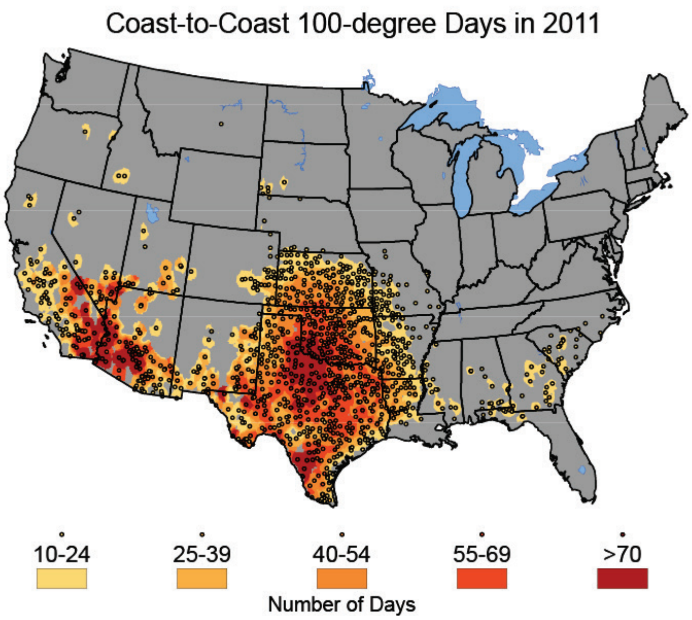

Figure 10.1: Coast-to-Coast 100-degree Days in 2011

Caption: Map shows the distribution of places around the country with days having high temperatures of 100ºF or more during the record-setting summer of 2011. The record temperatures and drought during the summer of 2011 represent conditions that will be more likely in the U.S. as climate change continues.

(Source: NOAA NCDC, 2012).

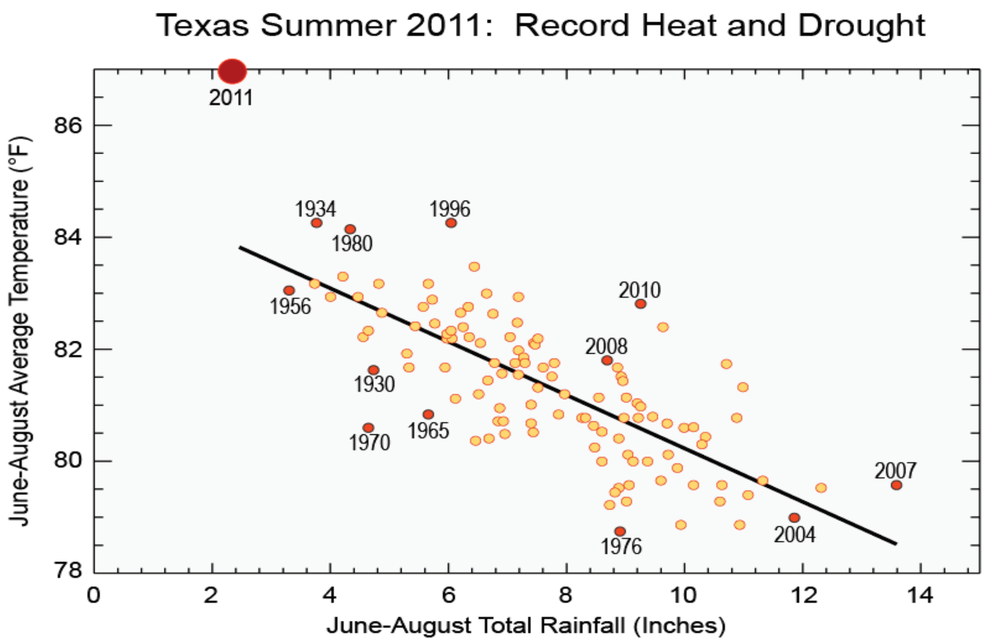

Figure 10.2: Texas, Summer 2011: Record Heat and Drought

Caption: Graph shows average summer temperature and total rainfall in Texas from 1919 through 2011. The record temperatures and drought during the summer of 2011 (red dot) represent conditions far outside those that have been registered since the instrumental record began (NCDC 2012). An analysis has shown that the probability of such an event has more than doubled as a result of human-induced climate change (Hoerling et al. 2012).

The impacts on land resources and land use were dramatic. Drought reduced crop yields and affected livestock, costing Texas farmers and ranchers more than $5 billion, a 27.7% loss compared to average revenues of the previous four years (Fannin 2011). With increased feed costs, ranchers were forced to sell livestock at lower value. Drought increased tree mortality (TFS 2011a), providing more fuel for record wildfires that burned 3.8 million acres (an area about the size of Connecticut) and destroyed 2,763 homes (TFS 2011b).

Energy, water, and land interactions complicated and amplified these impacts. With electricity demands at all-time highs, water shortages threatened more than 3,000 megawatts of generating capacity—enough power to supply more than one million homes (Smith 2011). As a result of record electricity consumption, marginal prices repeatedly hit $3,000 a megawatt hour, which is three times the maximum amount that generators can charge in deregulated electricity markets in the eastern U.S. (Giberson 2011). More than 16% of electricity production relied on cooling water from sources that shrank to historically low levels (ERCOT 2011), and water used to generate electricity competed with simultaneous demands for agriculture and other human activities.

City and regional managers rationed water to farms and urban areas, and in some instances, water was trucked to communities that lacked sufficient supplies (Fernandez 2012). As late as November 2011, about 20% of Texas public water systems were still affected by water restrictions. At the same time, changing vegetation attributes, grazing, cropping, and wildfire compromised water quality and availability, requiring more power for water pumping and purification. One community banned water use for shale gas extraction, and biofuel production was constrained.

The co-occurrence of a heat wave and drought could play out differently in other parts of the country because of relative differences in the manifestation of climate change impacts on energy, water, and land resources and in the manmade infrastructure. For example, sustained drought events in the Pacific Northwest will affect electricity supply directly by reducing hydropower resources and pose challenges for ecosystem services. Hydropower is increasingly being used to balance intermittent wind generation in the Northwest and seasonal hydroelectric restrictions have already created challenges to fulfill this role. Drought in the Midwest poses challenges to meeting electricity demands because diminished water availability and elevated water temperatures reduce the efficiency of electricity generation. Temporary plant shutdowns are mandated in many states if the temperature of water returned to streams after being used to cool power plants exceeds thresholds protecting water quality.

Interactions of Water, Energy, and Land Uses

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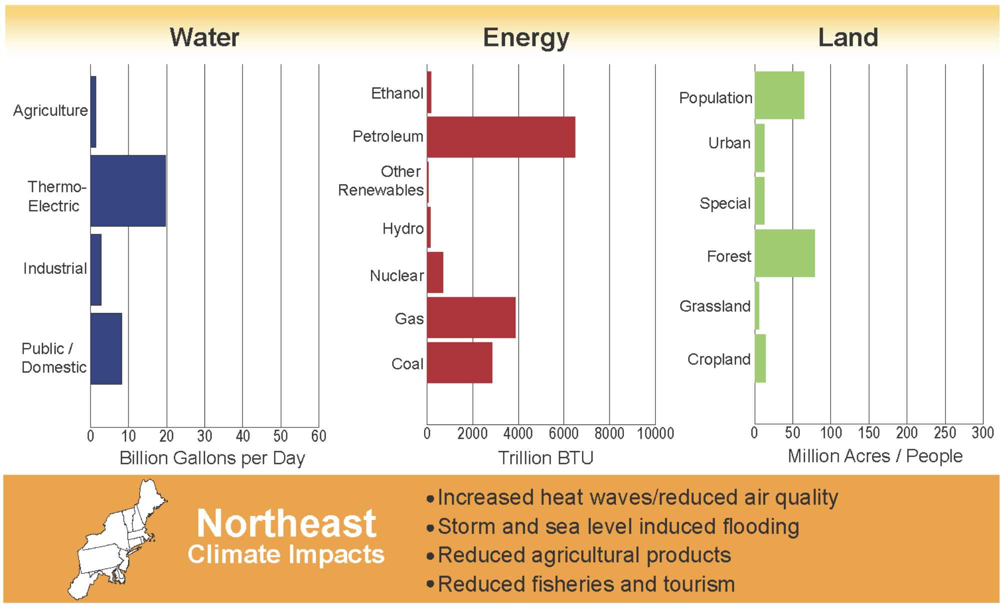

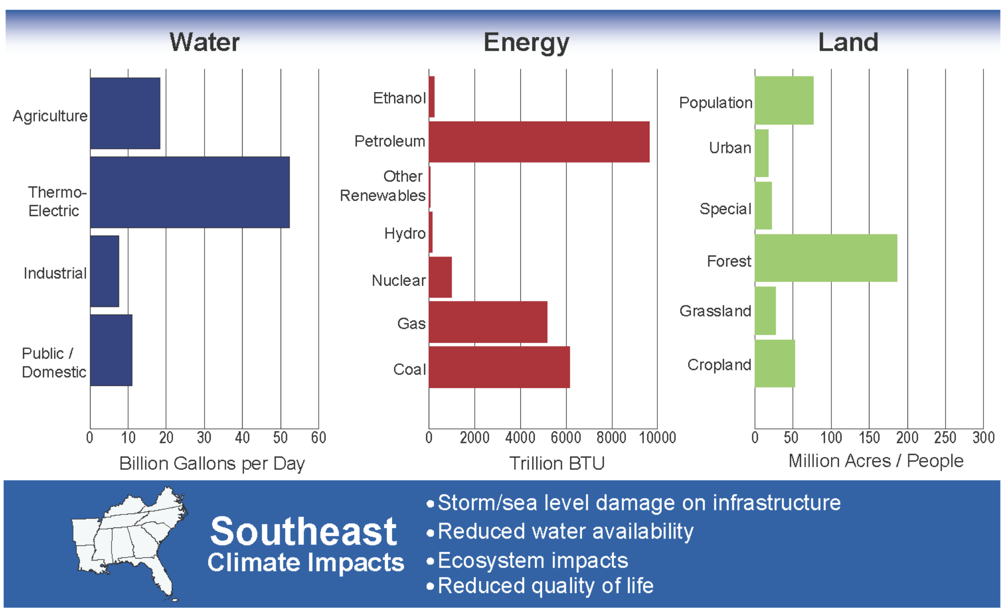

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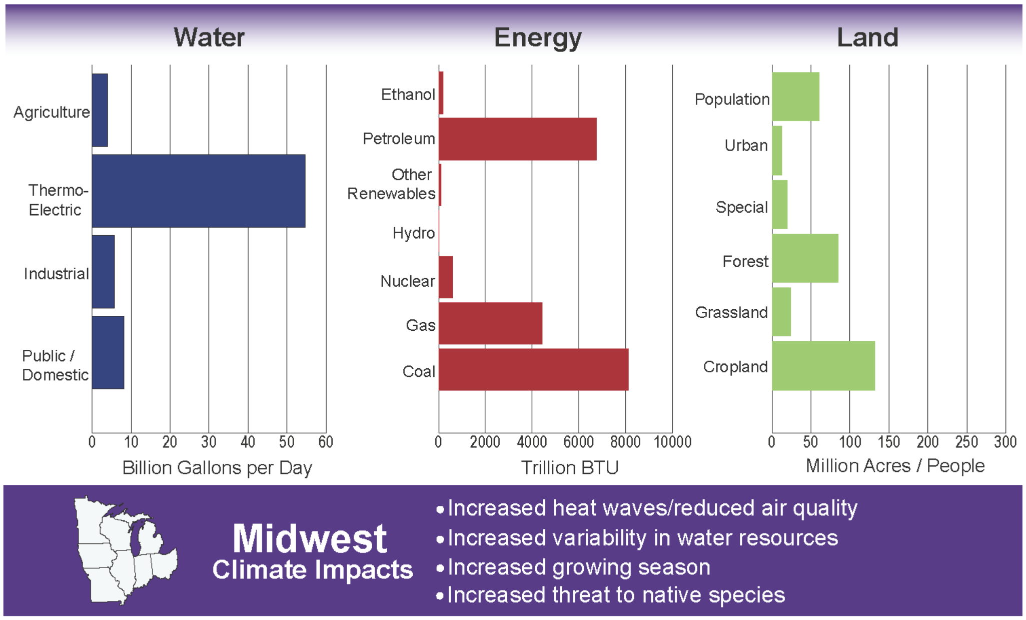

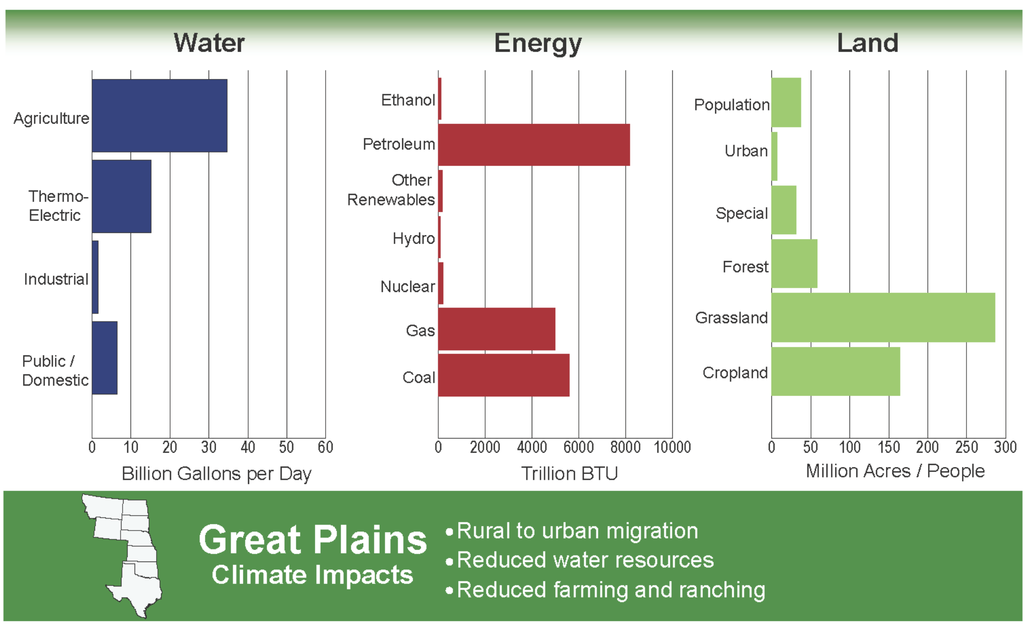

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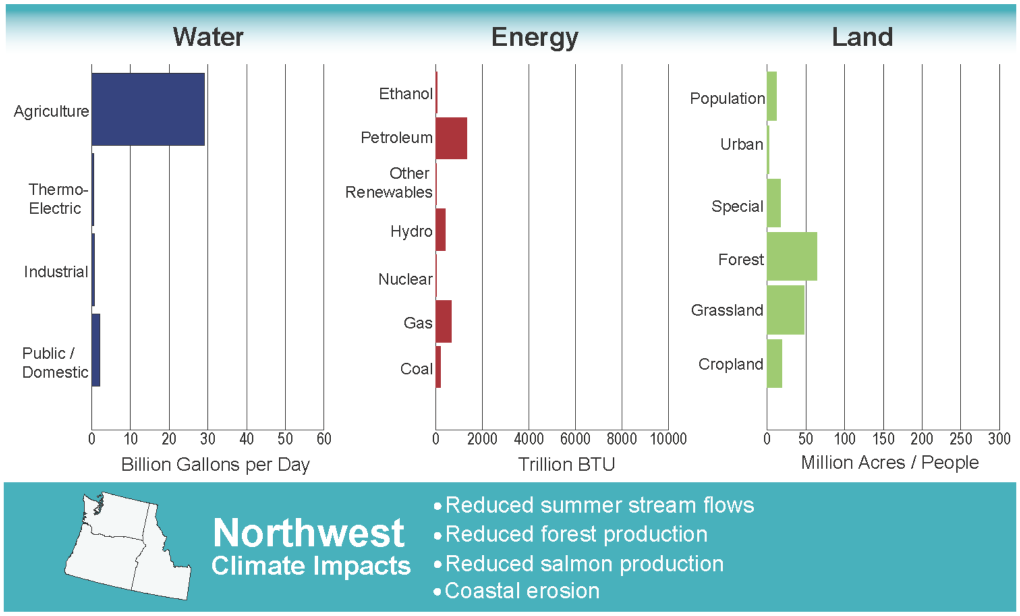

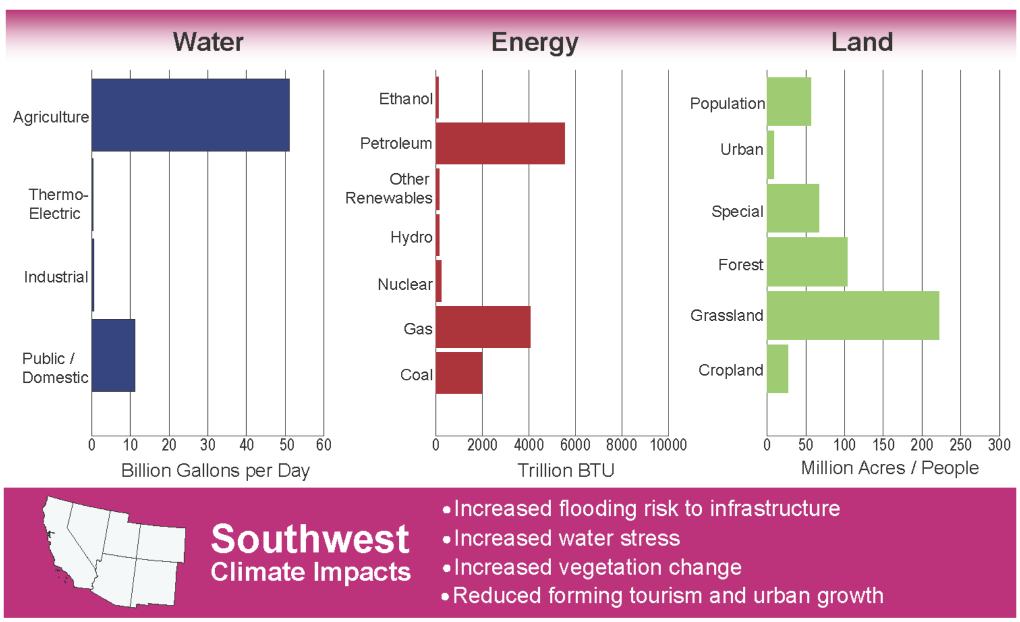

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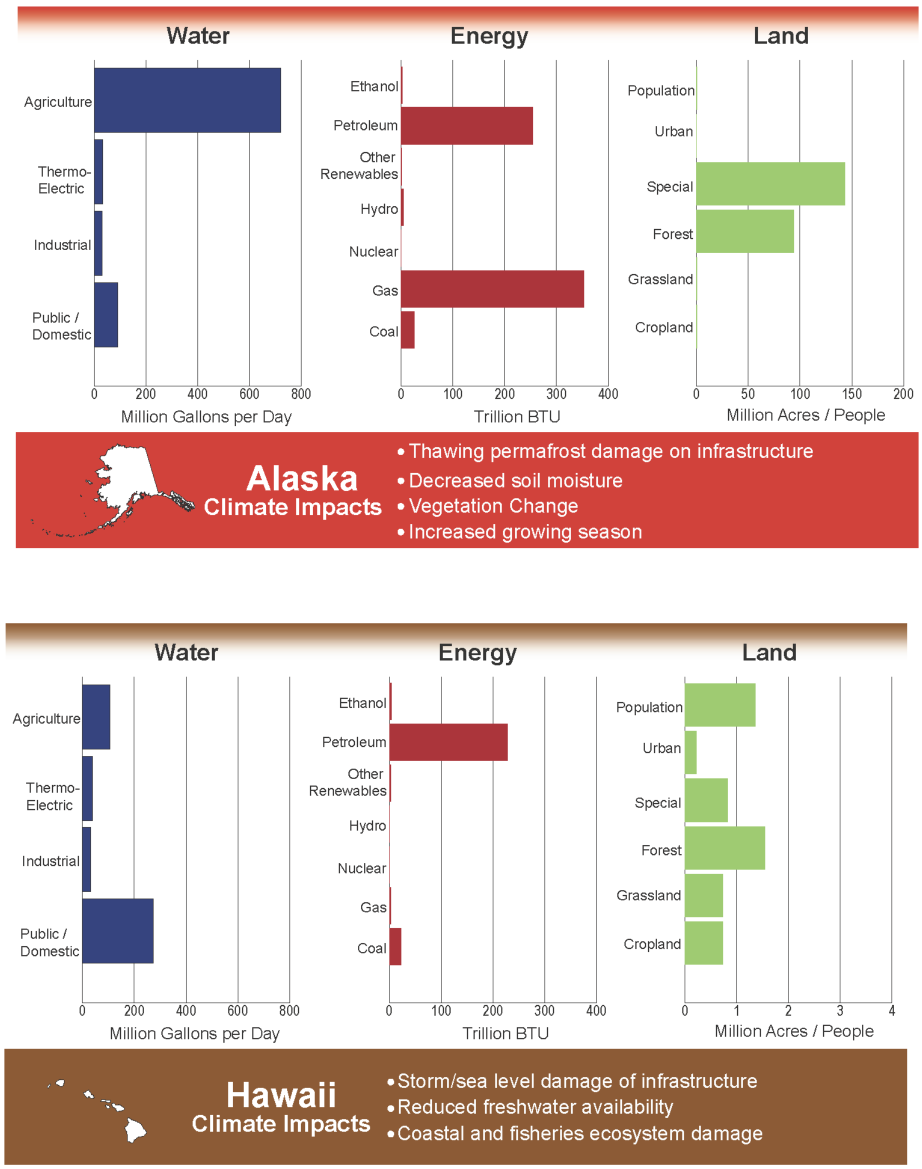

Figure 10.3: Interactions of Water, Energy, and Land Uses

Caption: Breakout of unique regional characteristics of current use of land, energy, and water in the context of climate change. There is significant regional variation in how water is used in each region, notably the relative amounts used for agriculture and energy production. Energy mix also varies by region, with all regions showing a high reliance on petroleum and other fossil fuels. Agriculture includes irrigation, livestock, and aquaculture uses. (Sources: Energy data from EIA 2012; Water data from Kenny et al. 2009; Land data from USDA ERS 2007)

Options for Reducing Emissions

The dependence of energy systems on land availability and water supplies will influence their development and constrain some options for reducing greenhouse gas emissions.

Energy systems vary widely in their use of land and water. The chart below provides a perspective on water withdrawals and consumptive use, illustrating the wide variation across both generation technologies and the accompanying cooling technologies. Energy technology choices today are strongly influenced by water and land considerations. Land and water influences on energy production capacity are expected to get stronger in the future.

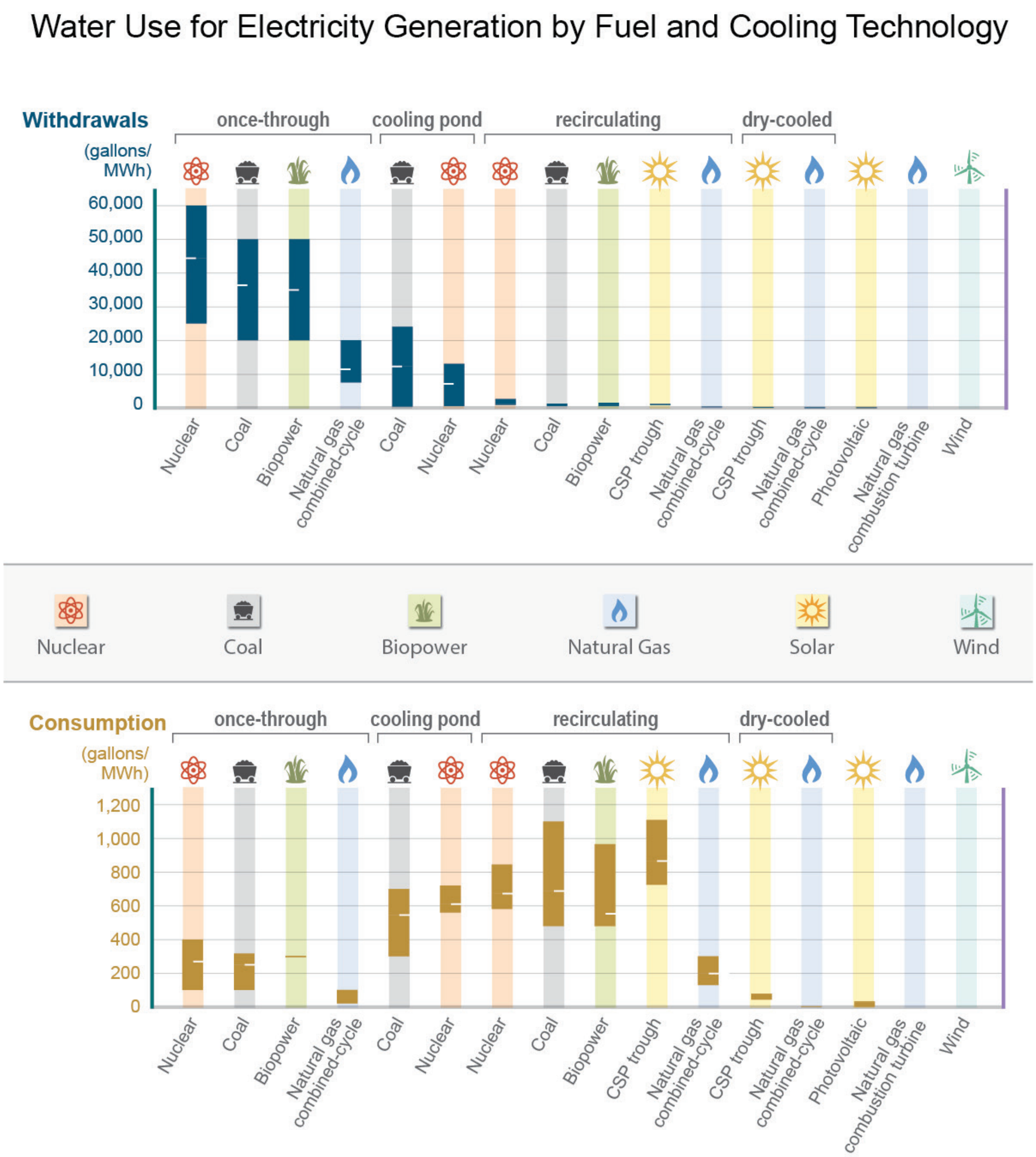

Figure 10.4: Water Use for Electricity Generation by Fuel and Cooling Technology

Caption: Technology choices can significantly affect both water withdrawals and consumption. For example, using cooling ponds versus once-through cooling for nuclear power generation can dramatically reduce water withdrawal from streams and rivers, but increases the amount of water consumed. Ranges reflect minimum and maximum amounts of water used for selected technologies.

Top panel shows water withdrawals for various electricity production methods. Some methods, like most conventional nuclear power plants that use “once-through” cooling systems, require large water withdrawals, and return most of that water to the source (usually rivers and streams). For nuclear plants, utilizing cooling ponds can dramatically reduce water withdrawal from streams and rivers, but increases the total amount of water consumed.

Bottom panel shows water consumption for various electricity production methods. Coal-powered plants using recirculating water systems have relatively low requirements for water withdrawals, but consume much more of that water, as it is turned into steam. Water consumption for various dry-cooled electricity generation is negligible.

(Source: Averyt et al. 2011; Macknick et al. 2011).

Technological advances create opportunities to take advantage of energy resources with reduced greenhouse gas emissions. Today, recent advances in natural gas extraction methods are providing low-cost, potentially abundant fuel for electricity generation with significantly reduced carbon dioxide emissions compared to coal-fired power plants. With substantial changes to the U.S. power system, renewable energy, including solar, wind, and biofuels, could meet a considerable fraction of the nation's demand for electricity in 2050 (Mai et al. 2012) with significantly reduced greenhouse gas emissions. Over the longer term, carbon dioxide capture and storage (CCS) technologies could play a key role in reducing emissions from fossil fuel use, but costs could be prohibitive (Ranjan and Herzog 2011). In combination with biofuels, however, costs of CCS technologies are reduced and may even provide a means of reducing atmospheric CO_2 levels (Keith et al. 2006; Lackner 2009).

The availability of water and/or land resources will impact design choices and operations of these technologies in the future and, in some cases, constrain their deployment. Changing climate conditions have the potential to intensify these effects. The following sections discuss energy, land, and water interactions for four key emerging or future technologies for reducing carbon emissions – natural gas from shale, solar power, biofuels, and CCS – and describe some of the technology options for addressing challenges that arise from these interactions.

Natural Gas

Natural gas provides a fossil fuel alternative to coal production with reduced carbon dioxide emissions. During 2010, U.S. natural gas production was the highest recorded since 1973 (EIA 2011). Horizontal drilling and hydraulic fracturing made possible much of this growth in domestic gas production. These techniques enable extraction of natural gas trapped in shale formations: fine-grained sedimentary rocks that are often rich sources of petroleum and natural gas. Horizontal wells sometimes extend 5,000 feet or more through a shale deposit. Hydraulic fracturing breaks apart relatively impermeable shale, allowing gas to flow into wells (Figure 4).

The U.S. Energy Information Administration projects a 29% increase in U.S. natural gas production by 2035, with lower CO_2 emissions where natural gas displaces other fossil fuels (EIA 2012). A natural gas combined-cycle power plant emits about 50% less CO_2 than does a modern coal plant. The projected increases in natural gas production would lead to a significant reduction in U.S. greenhouse gas emissions over other fossil fuel alternatives.

Hydraulic fracturing for shale gas production requires significant amounts of water. A typical horizontal well for shale gas production requires from 2.5 to 5 million gallons of water, frequently from streams, reservoirs, or groundwater (DOE 2009a), but also from private water, municipal and re-used produced water (http://www.naturalgas.org/shale/waterrequirements.asp). While not large compared to many other water demands, this water use can become an issue in specific locations. As the suspension of shale gas extraction activities in Texas during the 2011 drought demonstrated, in regions where climate change leads to drier conditions, hydraulic fracturing is vulnerable to climate-change related reductions in water supply, at least during times of water stress or limited water availability. The gas extraction industry has begun reusing water in order to lower demand. After the hydraulic fracture is made, gas and water are produced from the well. The produced water is a combination of water, chemicals, and sand that were injected, and local formation water that may contain radioisotopes and other compounds. The produced water stream may require treatment depending on whether it is re-injected or discharged to surface water. Recycling the water becomes more difficult as salts and other contaminants build up in the water with each reuse. Typically, flow-back water can be reused 3 to 4 times, but in some situations, it can be reused as many as 8 times (http://lingo.cast.uark.edu/LINGOPUBLIC/natgas/wellprod/index.htm), significantly reducing water demands.

The chemicals involved in hydraulic fracturing – both those injected and the natural elements in the produced water – have raised water quality concerns. Federal government and state-led efforts are underway to identify, characterize, and if necessary, find approaches to address these issues. At the federal level, the U.S. EPA has developed a 3-year research plan to study potential impacts on drinking water quality across the country (EPA 2011). In addition, regulatory and government agencies in a number of states have joined forces to create FracFocus.org – a public website for providing information on hydraulic fracturing and groundwater protection. Eight states have adopted the FracFocus system for official reporting of chemicals used in hydraulic fracturing.

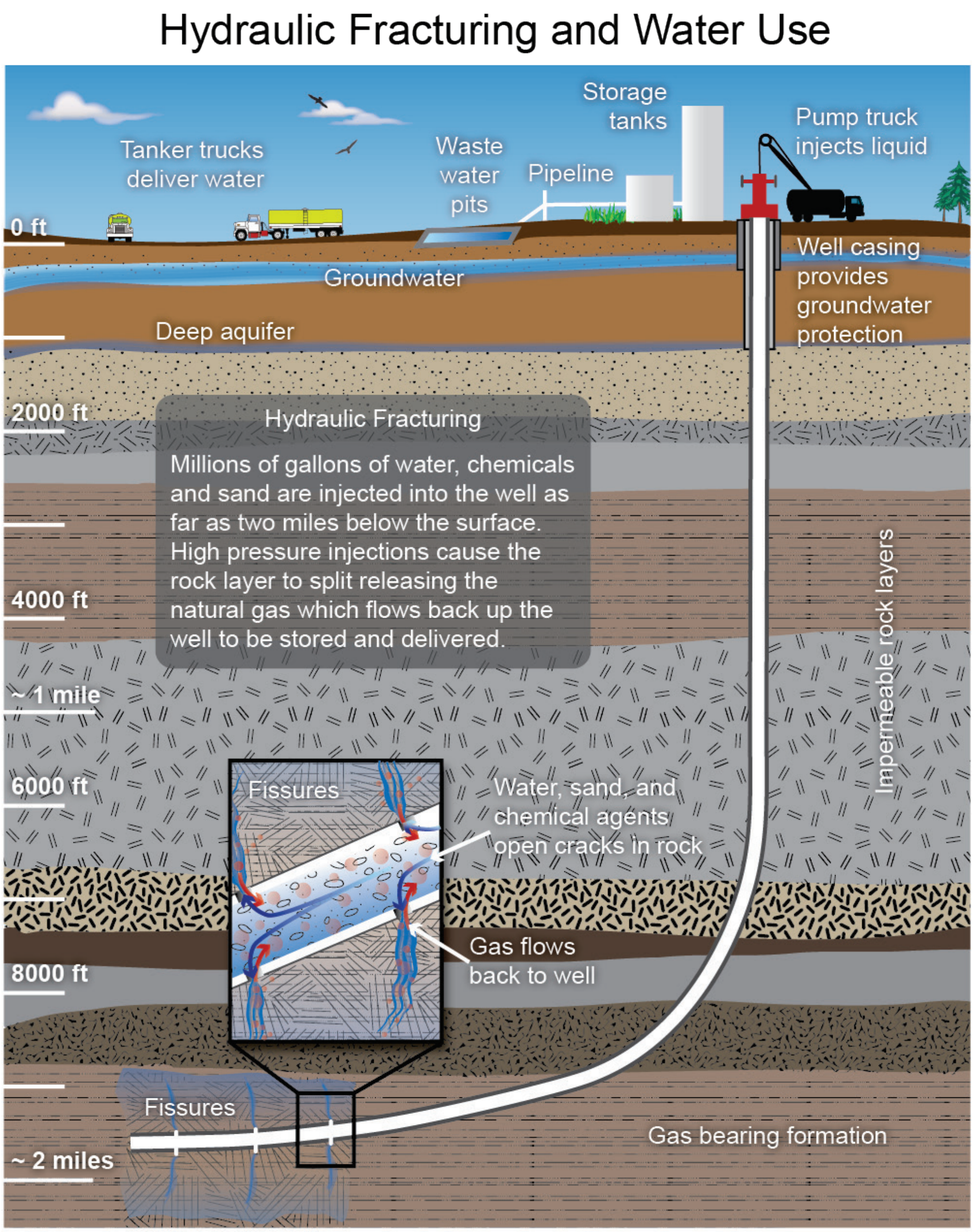

Figure 10.5: Hydraulic Fracturing and Water Use

Caption: Hydraulic fracturing, a drilling method used to retrieve deep reservoirs of natural gas, uses large quantities of water, sand, and chemicals that are injected at high pressure into horizontally drilled wells as deep as 10,000 feet below the surface. The pressurized mixture causes the rock layer to crack. Sand particles hold the fissures open so that natural gas from the shale can flow into the well. Questions about both the water quantity necessary for this extraction method, as well as the potential to affect water quality, have produced national debate about this method.

The competition for water is expected to increase in the future. State and local water managers will need to assess how gas extraction competes with other priorities for water, such as water for other energy production, irrigation, municipal supply, industry use, and livestock production. Collectively, such interactions between the energy and water resource sectors increase vulnerability to climate change, particularly in water-limited regions that are projected to, or become, significantly drier.

Solar Power Generation

Efficient solar power requires long days with few clouds. Such conditions are prominent across the Southwest U.S., and, with few exceptions, current and pending utility-scale solar facilities are located in the Southwest where sparsely populated land is available. Climate change, however, is projected to affect surface and groundwater supplies within this already arid region (see Ch. 20: Southwest).

Renewable Energy and Land Use

Figure 10.6: Renewable Energy and Land Use

Caption: Photovoltaic panels convert sunlight directly into electricity. Utility-sized solar power plants require large tracts of land.

(Source: Duke Energy, under a creative commons license http://www.flickr.com/photos/dukeenergy/5187413025/)

Solar energy technologies have the potential to satisfy a major portion of U.S. electricity demands as an alternative to fossil fuels, reducing greenhouse gas emissions. But utility-scale solar power systems require substantial land, and at least in the case of solar thermal facilities, water is also required. A recent Department of Energy study concluded that meeting 14% of the U.S. demand for electricity with solar power by 2030 could require twice the land area of Delaware and, depending on the cooling technology, significant water resources (DOE 2012).

The land and water requirements for solar energy systems vary substantially among technologies. For utility-scale electricity generation, photovoltaic systems require 3 to 10 acres per megawatt (MW) of generating capacity and consume as much as 5 gallons of water per megawatt hour (MWh) of electricity production. Another technology for utility-scale electricity generation – concentrating solar systems, requires up to 15 acres per MW and wet cooling consumes 1,040 gallons of water per MWh (DOE 2012). Land and biodiversity constraints were amply illustrated with the suspension of a concentrating solar power (CSP) farm, the $2.2B BrightSource Energy solar farm in the Ivanpah Valley, CA, when desert tortoise relocation and protection cost the company as much as $40M (Cart 2012; Wang 2011). At this time, construction for the Ivanpah project is proceeding (Fehrenbacher 2012).

One of the world's largest concentrating solar systems, Solar Energy Generating Systems (SEGS), located in California's Mojave Desert, uses water for cooling as well as to produce steam for electricity generation. But recognizing water limitations and the need for cooling, most large-scale solar systems now in planning or development will be dry cooled and will rely on molten salt or other materials for heat transfer, substantially reducing water demands. Although warmer air resulting from climate change will reduce the efficiency of electricity production, these newer solar systems will be less vulnerable to the drier conditions projected to occur in the region with climate change. However, dry cooling systems are more expensive and result in lower plant thermal efficiency. Dry cooling systems also have a higher upfront capital cost than wet systems and require a significant amount of energy to operate. The Beacon solar energy project (WorleyParsons Group Inc. 2008) reported that air cooling resulted in a "parasitic" loss of 7.5% of net electricity produced, and hybrid cooling (a combination of dry and wet cooling) technologies led to a 4.6% loss. Moreover, the losses are greater on hot days— typically when and where peak power is most in need (DOE 2009b; Maulbetsch and DiFilippo 2006). Thus plant designs will have to carefully balance cost, operating issues, and water availability.

Biofuels

Biofuels made from grains, sugar and oil crops, starch, grasses, trees, and biological waste can reduce U.S. dependence on foreign energy resources, while reducing greenhouse gas emissions. Under the Renewable Fuel Standard (RFS2), which is overseen by the EPA, there is a production goal of 36 billion gallons of biofuels annually by 2022, including 16 billion gallons of cellulosic biofuel, 15 billion gallons of conventional biofuels (mostly corn-based ethanol), and at least 1 billion gallons of biodiesel (EPA 2012). The remaining amount of the goal will be satisfied by the Advanced Biofuel Requirement, which is expected to be mostly sugarcane ethanol from Brazil (NRC 2011).

Currently, most U.S. biofuels, primarily ethanol and diesel fuel, are produced from edible parts of corn grown on rain-fed land. About 40% of the 2011 U.S. corn crop was used to produce more than 13 billion gallons of ethanol, which helped satisfy around 10% of U.S. gasoline demand. While ethanol production competes with food production and other uses of corn, the fermentation process used to create ethanol produces a variety of economically valuable co-products. For example, dried distillers' grains (DDGs), a direct byproduct of corn ethanol production, are an important component of animal feed (NRC 2011; USDA ERS 2011). In the U.S., about 50% of biodiesel is made from soybeans, with the rest made from animal fats, recycled fats and oils, and other crop oils. However, total U.S. biodiesel production is much lower than ethanol production, and is very limited compared to other parts of the world where diesel engines are more common

Approximately 40 million acres of cropland in the United States were used for ethanol production in 2011, roughly 16% of the land planted to the eight major field crops (USDA 2012).

Several long-term factors influence commodity and food prices, including global growth in population and per capita incomes, related increases in world per capita consumption of animal products, depreciation of the U.S. dollar, rising energy prices, and expansion of global biofuel production that is more rapid than overall growth in agricultural productivity. Recent crop price increases have been driven by a series of adverse weather events in a number of major world producing regions that occurred in a relatively compressed time period from June 2010 to April 2011 (Trostle et al. 2012). Biofuels have the potential to provide net environmental benefits compared to petroleum-based fuels. However, the extent of these benefits depend on many site-specific factors: the type of feedstock, management practices used to produce them, prior land use, and land-use changes caused by their production. For example, biofuel production has been cited for contributing to harmful algal blooms, eutrophication (an influx of nutrients that can lead to the excessive growth of algae), and hypoxic conditions (oxygen-depleted "dead zones") in the Gulf of Mexico and elsewhere (NRC 2011). Consumptive water use over the life cycle of corn-grain ethanol varies widely, from 15 gallons of water per gallon of gasoline equivalent for rain-fed corn-based ethanol in Ohio, to 1,500 gallons of water per gallon of gasoline equivalent for irrigated corn-based ethanol in New Mexico; in comparison, petroleum-based fuels use 1.9 to 6.6 gallons of water per gallon of gasoline (NRC 2011).

Looking forward, the current production level of conventional corn-based ethanol is very close to its RFS2 target level of 15 billion gallons annually. The greatest expansion is targeted for cellulosic biofuels – biofuels derived from the entire plant rather than just the food portions, principally cellulose, hemicelluloses, or lignin. No commercially viable refineries currently exist for cellulosic biofuel production (though several commercial refineries are in development in the U.S.), and the estimated cost of producing cellulosic ethanol is currently much higher than the cost of corn ethanol (NRC 2011). Cellulosic feedstocks necessary to meet the aggressive RFS2 target of 16 billion gallons annually could require an additional 30 to 60 million acres of land (NRC 2011). Additionally, cellulosic biomass potentially has several advantages over corn, including fewer water quality concerns (for example, Costello et al. 2009), less water consumption, and the potential for use of forest products (NRC 2011).

To the extent that further expansion of land for biofuel feedstock production is located in more arid, less arable regions, irrigation and fertilizer uses will increase (Graham-Rowe 2011). The impacts of climate change (See Ch. 2: Our Changing Climate, Ch. 3: Water Resources, and Ch. 6: Agriculture), however, may make it increasingly difficult to raise crops in arid regions of the country. The use of crops such as switchgrass that are better suited to arid conditions and are efficient in recycling nutrients can reduce the vulnerability of biofuel production to climate change.

Carbon Dioxide Capture and Storage

Carbon capture and storage (CCS) technologies have the potential to reduce emissions from coal- and natural gas-fired plants by 90%, allowing continued use of fossil fuel in a carbon-constrained future. In addition, capturing and storing carbon dioxide emissions from the combustion of biofuels represents one of very few potential options for reducing atmospheric CO_2 (IPCC 2005). Carbon from the atmosphere accumulates in growing plants that are used to produce a biofuel. When the biofuel is combusted, the CO_2 is captured and stored, constituting a net removal of CO_2 from the atmosphere for as long as storage continues and the standing stock of plants is sustained.

CCS substantially increases the cost of building and operating a power plant. In addition to the upfront capital expense, the CCS process requires about 15% to 30% of the plant output to operate. Substantial amounts of water are also used to separate CO_2 from emissions (Newmark et al. 2010). However, the technology is just emerging. The only facilities currently operating are at the pilot scale, and many opportunities exist to reduce these impacts. For example, gasification technologies, where coal or biomass are converted to gases and CO_2 is separated before combustion, reduce the energy penalty and water requirements but currently have higher capital costs. Thus, as with solar power, technology and design choices for CCS need to be balanced with water requirements when deployed in dryer regions.

Challenges to Reducing Vulnerabilities

Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is difficult, but can improve the analysis of options for reducing climate change impacts.

Because of the complex nature of the interactions among land, energy, and water systems, considering the complete picture of climate impacts and potential adaptations can help provide better solutions. The Columbia River basin is one example of an area where risks, vulnerabilities, and opportunities are being jointly considered. The Columbia River is the fourth largest river on the continent, crossing the U.S. and Canadian border, and drives the production of more electricity than any other river in North America. Approximately 15% of the Columbia River Basin lies within British Columbia (Figure 8), but an average of 30% of the total average discharge originates from the Canadian portion of the watershed. To provide flood control for the U.S. and predicted releases for hydropower generation, the Columbia River system is managed through a treaty that established a cooperative agreement between the U.S. and Canada to regulate the river for these two uses (Center for Columbia River History 2012). The basin also supports a range of other uses, such as navigation, irrigation, fish and wildlife habitat, recreation, and water resources for agricultural, industrial, and individual use. For all multi-use river basins, understanding the combined vulnerability of water, energy, and land use to climate change is essential to planning for water management and climate change adaptation.

The National Climate Assessment climate outlook for the Northwest shows a warmer annual and drier summer climate (Ch. 21: Northwest), potentially affecting both the timing and amounts of water availability. For example, if climate change reduces streamflow at certain times, fish and wildlife, as well as recreation, may be vulnerable (Dalton et al. 2012). Climate change stressors will also increase the vulnerability of the region's vast natural ecosystems and forests in multiple ways (see Ch. 7: Forests and Ch. 8: Ecosystems). Currently, only 30% of annual Columbia River Basin runoff can be stored in reservoirs (Bruce et al. 2003). Longer growing seasons might provide opportunities for greater agricultural production, but the projected warmer and drier summers could increase demand for water for irrigation, perhaps at the expense of other water uses due to storage limitations. Wetter winters might offset increased summer demands, but existing hydropower storage capacities were not designed to accommodate significant increases in winter precipitation.

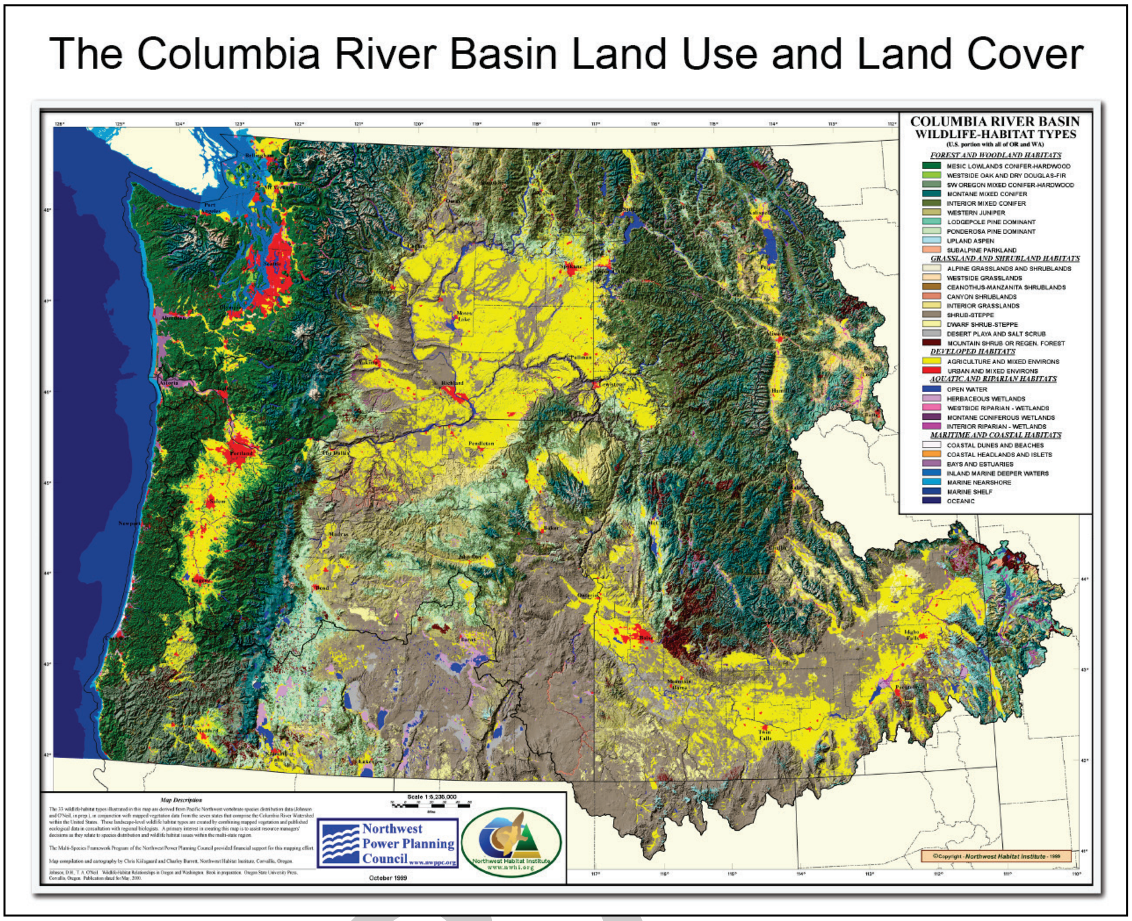

Figure 10.7: The Columbia River Basin Land Use and Land Cover

Caption: Agriculture is in yellow, forests are shades of green, shrublands are gray, and red are urban areas. The river is used for hydropower generation, flood control, agriculture irrigation, recreation, support of forest and shrubland ecosystems, and fish and wildlife habitat. Climate change may impact the timing and supply of the water resources, affecting the multiple uses of this river system.

(See http://www.nwcouncil.org/library/2003/2003-14/default.htm).

Conclusions

A changing climate, particularly in areas projected to be warmer and drier, is expected to lead to drought and stresses on water supply, impacting energy, water, and land sectors in the U.S. But the risks associated with these impacts are not isolated to individual sectors. As the Texas drought of 2011 illustrates, impacts to a particular sector, such as energy production, generates consequences for the others, such as water resource availability. Similarly, new energy development and production will require careful consideration of land and water sector resources. As a result, vulnerability to climate change depends on the intersecting risks within and among all three sectors. Understanding of this cross-sector nature of climate change impacts is improving, and assessments will increasingly evaluate risks and vulnerability from this standpoint.

Water Stress in the U.S.

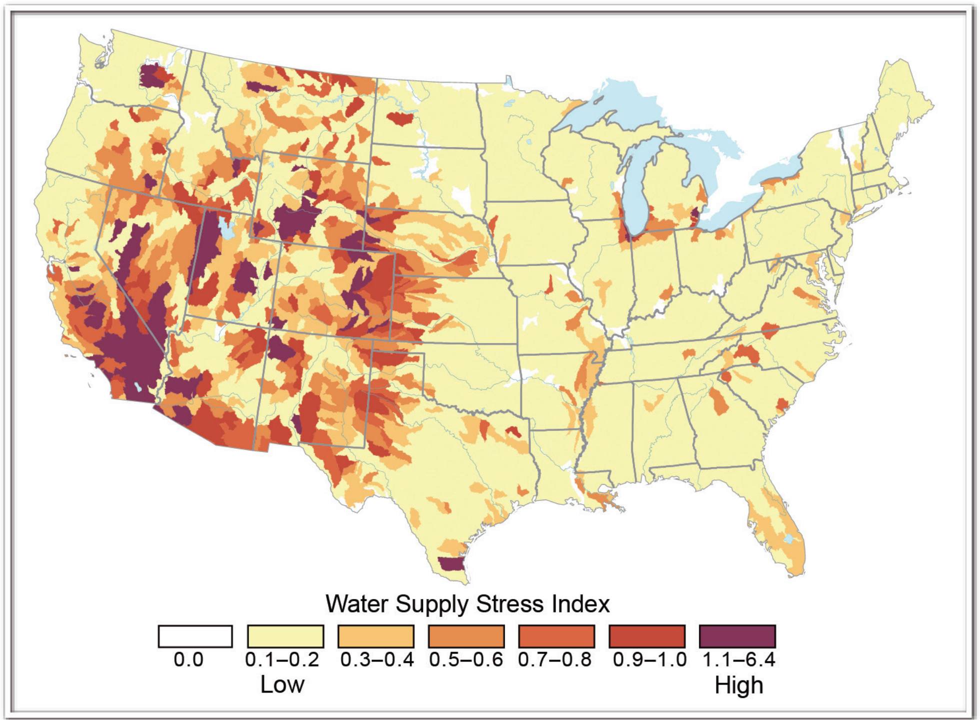

Figure 10.8: Water Stress in the U.S.

Caption: In many parts of the country, competing demands for water create stress in local and regional watersheds. Map shows a "water supply stress index" for the U.S. based on observations, with widespread stress in much of the Southwest, western Great Plains, and parts of the Northwest (Averyt et al. 2011). Watersheds are considered stressed when water demand (by power plants, agriculture and municipalities) exceeds 40% of available supply.

The complex nature of interactions among land, energy, and water systems, particularly in the context of climate change, does not lend itself to simple solutions. Interactions between water and energy will vary among regions, with water being too scarce in some regions, too abundant in others, or too warm to meet thermal regulations for discharge water used for power plant cooling. Similarly, land-use issues, like those identified in the temporary suspension of concentrating solar power systems to address environmental concerns, will also require joint consideration. The complex nature of water and energy systems are also highlighted in Chapter 3 (Water Resources), which discusses water constraints in the southern states and across the Southwest, and in Chapter 4 (Energy Supply and Use), where it is noted that there will be challenges across the nation for water quality to comply with thermal regulatory needs for energy production.

Adaptation to climate change occurs in large part locally or regionally, and conflicting stakeholder priorities, institutional commitments, and international agreements have the potential to complicate or even compromise adaption strategies with regard to energy, water, and land resources. Effective adaptation to the impacts of climate change requires a better understanding of the interactions between the energy, water, and land resource sectors. Whether managing for water security in the context of energy systems, or land restrictions, or both, an improved dialogue and between the scientific and decision-making communities will be necessary to understand tradeoffs and compromises needed to manage and understand this complex system. This will require not only integrated and quantitative analyses of the processes that underlie the climate and natural systems, but also an understanding of decision criteria and risk analyses to communicate effectively with stakeholders and decision-makers.

Traceable Accounts

Chapter 10: Water, Energy, and Land Use

Key Message Process: The authors met for a one-day face-to-face meeting and held teleconferences approximately weekly from March through August 2012. They considered a variety of technical input documents, including a document prepared through an interagency process, Skaggs et al., 2012, and a number of other reports submitted through the Federal Register Notice request for public input. The key messages were selected based on expert judgement, derived from the set of examples assembled to demonstrate the character and consequences of interactions between the water, energy, and land resource sectors.

Key message #1/3	Energy, land, and water systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate vulnerability as well as adaptation and mitigation options for different regions of the country.
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the water, energy, and land use Technical Input (Skaggs et al. 2012) Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. Report No. PNNL-21185, Pacific Northwest National Laboratory, Richland, WA.). Technical Input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. A technical input report prepared for the NCA by the Department of Energy describes the framework within which the energy, water, and land resource sectors interact (Skaggs et al. 2012). While developing this technical input report, the author team convened a workshop of experts and stakeholders. The report incorporates the findings of the workshop. The report summarizes numerous examples of interactions between specific sectors, such as energy and water or water and land use. A synthesis of these examples provides insight into how climate change impacts the interactions between these sectors. Skaggs et al. (2012) show that the character and significance of interactions between energy, water, and land resource sectors vary regionally. Additionally, the influence of impacts on one sector within the others will depend on the specific impacts involved. Thus, as a general statement, the key message states that impacts affects these interactions, but does not state that this will occur in all circumstances. Chapter 10 uses the NCA Climate Scenarios (e.g., Kunkel et al. 2012) and in particular the climate outlooks where statements depend on potential climate change associated with different emissions levels. Regional climate outlooks are invoked by cross-reference to the appropriate regional chapter of the report. Chapter 10 provides an example of cascading effects by describing the consequences of drought across Texas during 2011 (Hoerling et al. 2012; NCDC 2012; Peterson et al. 2012). The Texas drought provides a clear example of cascading impacts through interactions among the water, energy, and land resource sectors (ERCOT 2011; Fannin 2011; Fernandez 2012; TFS 2011a, 2011b). The U.S. Drought Monitor (http://droughtmonitor.unl.edu/) provides relevant historical data. Articles appearing in the public press, on Internet media, in briefings to government institutions, and in various government reports characterize specific attributes and impacts of the Texas drought of 2011. Ken Kunkel and Laura Stevens, NOAA, National Climate Data Center, created Figure 1 based on historical data assembled by the Cooperative Observer Network of

	the National Weather Service. These data are the basis for many of the historic trends included in the NCA Climate Scenarios developed for this report.
New information and remaining uncertainties	There are no major uncertainties regarding this key message. There are major uncertainties, however, in the magnitude of impacts in how decisions in one sector might affect another, and the intensity of interactions will be difficult to assess under climate change.
Assessment of confidence based on evidence a	**High**. The primary limitation on the confidence assigned to this key message is with respect to its generality. The degree of interactions among the water, energy, and land sectors varies regionally as does the character and intensity of climate change. The Texas drought of 2011 demonstrates the occurrence of cascading impacts involving these sectors; however, the Texas example cannot be generalized to all parts of the country or to all instances of climate change. The technical input report by Skaggs et al. (2012) provides numerous additional examples and a general description of interactions that underlie cascading impacts between these resource sectors.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter: Water, Energy, and Land Use

Key Message Process: See KM #1

Key message #2/3	**The dependence of energy systems on land availability and water supplies will influence their development and constrain some options for reducing greenhouse gas emissions.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the water, energy, and land use Technical Input (Skaggs et al. 2012) Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. Report No. PNNL-21185, Pacific Northwest National Laboratory, Richland, WA.). Technical Input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. A technical input report to the NCA prepared for the Department of Energy describes the framework within which the energy, water, and land resource sectors interact (Skaggs et al. 2012). Synthesis and Assessment Product 2.1 of the Climate Change Science Program (Clarke et al. 2007) describes relationships among different future mixtures of energy sources and associated radiative forcing of climate change as a context for evaluating emissions mitigation options. Chapter 10 describes evolving water and land requirements of four energy technologies [natural gas (EIA 2012), solar power (DOE 2012), biofuels, and carbon dioxide capture and storage (IPCC 2005) that involve lower greenhouse gas emissions than, for example, coal-fired electricity production, or in the case of CCS, reduce emissions with potential to lower atmospheric CO2 levels (Mai et al. 2012). In each case, the dependence of these energy technologies on water and land resources raised issues about their deployment and resource priorities. The availability of water and land resources constrains the use of these technologies; however, in recent experience, technological advances have reduced dependence on water and allowed use of land less suitable to other purposes. Statements about energy production and use are derived from U.S. Government reports (EIA 2011, 2012) (DOE 2009b). The contributions of horizontal drilling and hydraulic fracturing to natural gas production are based on a brief article by EIA (EIA 2012) and a primer by DOE (2009a). Information about water and energy demands for utility-scale solar power facilities is derived from two major Department of Energy reports (DOE 2012; Mai et al. 2012). Distribution of U.S. solar energy resources is from Web based products of the National Renewable Energy Laboratory (http://www.nrel.gov/gis/).
New information and remaining uncertainties	There are no major uncertainties regarding this key message. As demonstrated by progress in development and deployment of the technologies described, potential constraints arise because of dependence on water and land resources that motivate advances in technology to reduced dependence or adjustments of priorities. There are uncertainties however, in how energy systems' dependence on water will be limited by other resources, such as land or economics on technological development.
Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of	**High**. The primary limitation on confidence assigned to this key message is with respect to its generality and dependence on technological advances. In the cases described, technological development is reducing water and land requirements. It is difficult to forecast success in this regard for technologies such as CCS that are still in early phases of development.

impact or consequence	

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter: Water, Energy, and Land Use

Key Message Process: See KM #1

Key message #3/3	**Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is difficult, but can improve the analysis of options for reducing climate change impacts**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the water, energy, and land use Technical Input (Skaggs et al. 2012) Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. Report No. PNNL-21185, Pacific Northwest National Laboratory, Richland, WA.). Technical Input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Chapter 10 demonstrates that interactions among water, energy, and land resource sectors can lead to stakeholder concerns that reduce options for reducing vulnerability and thus for adapting to climate change. The Columbia River System provides a good example (Bruce et al. 2003; Dalton et al. 2012).
New information and remaining uncertainties	There are no major uncertainties regarding this key message, however, the extent to which local, state and national policies will impact options for vulnerability options under climate change is highly uncertain.
Assessment of confidence based on evidence	**High**. The primary limitation on confidence assigned to this key message is with respect to its generality.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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11. Urban Systems, Infrastructure, and Vulnerability

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Key Messages

1. **Climate change and its impacts threaten the well-being of urban residents in all regions of the U.S. Essential local and regional infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts.**
2. **In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.**
3. **Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.**
4. **City government agencies and organizations have started urban adaptation efforts that focus on infrastructure systems and public health. However, these efforts face many barriers to implementing and incorporating wider governmental, general public, and private efforts.**

Climate change poses a series of interrelated challenges to the country's most densely populated places: its cities. The U.S. is highly urbanized, with about 80% of its population living in cities and metropolitan areas. Many cities depend on infrastructure, like water and sewage systems, roads, bridges, and power plants, that is aging and in need of repair or replacement. Rising sea levels, storm surges, heat waves, and extreme weather events will compound those issues, stressing or even overwhelming these essential services.

Cities have become early responders to climate change challenges and opportunities due to two simple facts: First, urban areas have large and growing populations that are vulnerable for many reasons to climate variability and change; and second, cities depend on extensive infrastructure systems and the resources that support them, which often extend to, or derive from, rural locations at great distances from urban centers.

Urban dwellers are particularly vulnerable to disruptions in essential infrastructure services, in part because many of these infrastructure systems are reliant on each other to function. For example, electricity is essential to power multiple systems, and a failure in the electrical grid can affect water treatment, transportation services, and public health. These infrastructure systems – lifelines to millions – will be affected by various climate-related events and processes.

As climate change impacts increase, climate-related events will have large consequences for significant numbers of people who live in cities or suburbs. These changing conditions also create opportunities and challenges for urban climate adaptation, and many cities have begun adopting plans to address these changes.

Urbanization and Infrastructure Systems

Climate change and its impacts threaten the well-being of urban residents in all regions of the U.S. Essential local and regional infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts.

Direct and interacting effects of climate change will expose people who live in cities across the U.S. to multiple threats. Climate changes affect the built, natural, and social infrastructure of cities, from storm drains to urban waterways to the capacity of emergency responders. The vulnerability of urban dwellers multiplies when the effects of climate change interact with pre-existing urban stressors – like deteriorating infrastructure, areas of intense poverty, and high population density.

Three fundamental conditions define the key connections among urban systems, residents, and infrastructure (Solecki and Rosenzweig 2012; Wilbanks et al. 2012). First, cities are dynamic, and are constantly being built and rebuilt through cycles of investment, disinvestment, and innovation. Second, infrastructure in many cities is currently aging, resulting in an increasingly fragile system. At both local and regional levels, infrastructure use often exceeds design standards and limitations, and cannot handle increasing demands without a decline in service. Third, urban areas present tremendous social challenges, given widely divergent socioeconomic conditions and dynamic residence patterns that vary in different parts of each city. Heightened vulnerability of coastal cities and other metropolitan areas that are subject to storm surge, flooding, or extreme climate events will exacerbate impacts on populations and infrastructure systems.

U.S. urban areas currently include approximately 245 million residents, and are expected to grow to 364 million by 2050 (U.S. Census Bureau 2008, 2010b, 2010c). Paradoxically, as the economy and population of urban areas grew in the past decades, the built infrastructure within cities and connected to cities deteriorated, becoming increasingly fragile and deficient (Solecki and Rosenzweig 2012; Wilbanks et al. 2012). Existing built infrastructure (such as buildings, energy, transportation, water, sanitation systems, etc.) is expected to become more stressed in its ability to support a good quality of life for urban residents in the next decades – especially when the impacts of climate change are added to the equation (McCrea et al. 2011). As infrastructure is highly interdependent, failure in particular sectors is expected to have cascading effects on most aspects of affected urban economies. As new climate adaptation plans are formed, further expansion of the U.S. urban landscape into suburban and exurban spaces is expected. Significant increases in the costs of infrastructure investments are also expected as population density becomes more diffuse (Burchell et al. 2002).

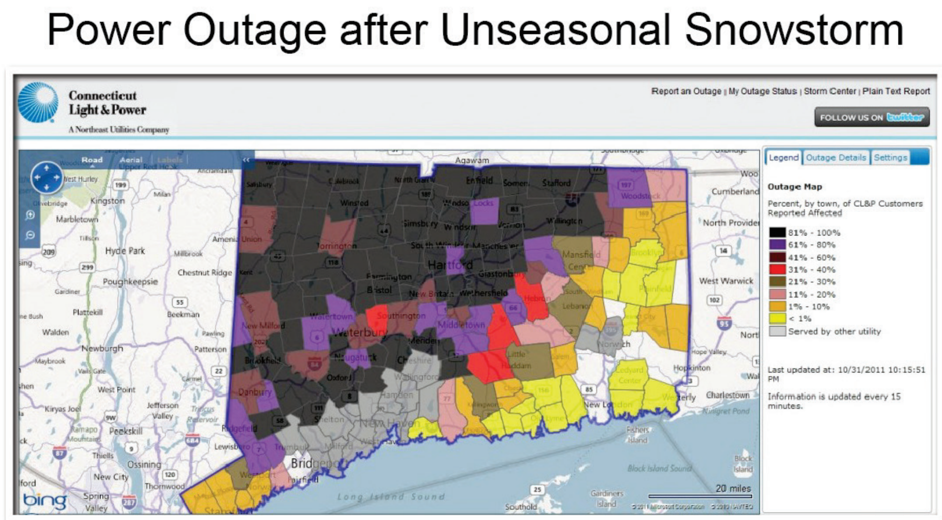

Figure 11.1: Power Outage after Unseasonal Snowstorm

Caption: Extreme weather events can affect multiple systems that provide services for millions of people in urban settings. Map here shows power outages for Connecticut Light & Power customers after an unusually strong October snowstorm, and just two months after Hurricane Irene hit the East Coast and disrupted power in late August 2011. (Figure source: Connecticut Light & Power.)

The vulnerability of different urban populations to hazards and risks associated with climate change depends on three characteristics: their exposure to particular stressors, their sensitivity to impacts, and their ability to adapt to changing conditions (Depietri et al. 2012; Douglas et al. 2011; Emrich and Cutter 2011). Climate change increases the frequency and intensity of extreme events like extremes of heat, heavy downpours, flooding from intense precipitation and storm surges, and disease incidence from temperature and precipitation changes. But as people begin to respond to new knowledge on climate change through the urban development process, social and infrastructure vulnerabilities can be altered (NPCC 2010). For example, the City of New York conducted a comprehensive review of select building and construction codes and standards in response to increased climate change risk in order to identify adjustments that could be made to increase climate resilience. Climate-change stressors will bundle with other socioeconomic and engineering stressors already connected to urban and infrastructure systems (Solecki and Rosenzweig 2012).

Essential Services are Interdependent

In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

Urban areas are linked with other areas through a complex set of infrastructure systems (CCSP 2008). For example, cities depend on other areas for supplies of food, materials, water, energy, and other inputs, and as destinations for products, services, and wastes. If infrastructure and other connections between source areas and cities are affected by climate change, then the dependent urban area also will be affected (Seto et al. 2012). Moreover, the economic base of an urban area depends on regional comparative advantage; therefore if competitors, markets, and/or trade flows are affected by climate change, a particular urban area also is affected (Wilbanks et al. 2012).

Urban vulnerabilities to climate change impacts are directly related to clusters of supporting resources and infrastructures located in other regions. For example, about half of the nation's oil refineries are located in only four states (Zimmerman 2006). Experience over the past decade with major infrastructure disruptions, such as the 2011 San Diego Blackout, the 2003 Northeast Blackout, and Hurricane Irene in 2011, has shown that the greatest losses from disruptive events may be distant from where damages started (Wilbanks et al. 2012). In another example, Hurricane Katrina disrupted oil terminal operations in southern Louisiana, not because of direct damage to port facilities, but because workers could not reach work locations through surface transportation routes and could not be housed locally because of disruption to potable water supplies, housing, and food shipments (Myers et al. 2008).

Although infrastructures and urban systems are often viewed individually – for example, transportation or water supply or wastewater/drainage – they are usually highly interactive and interdependent (Kirshen et al. 2008).

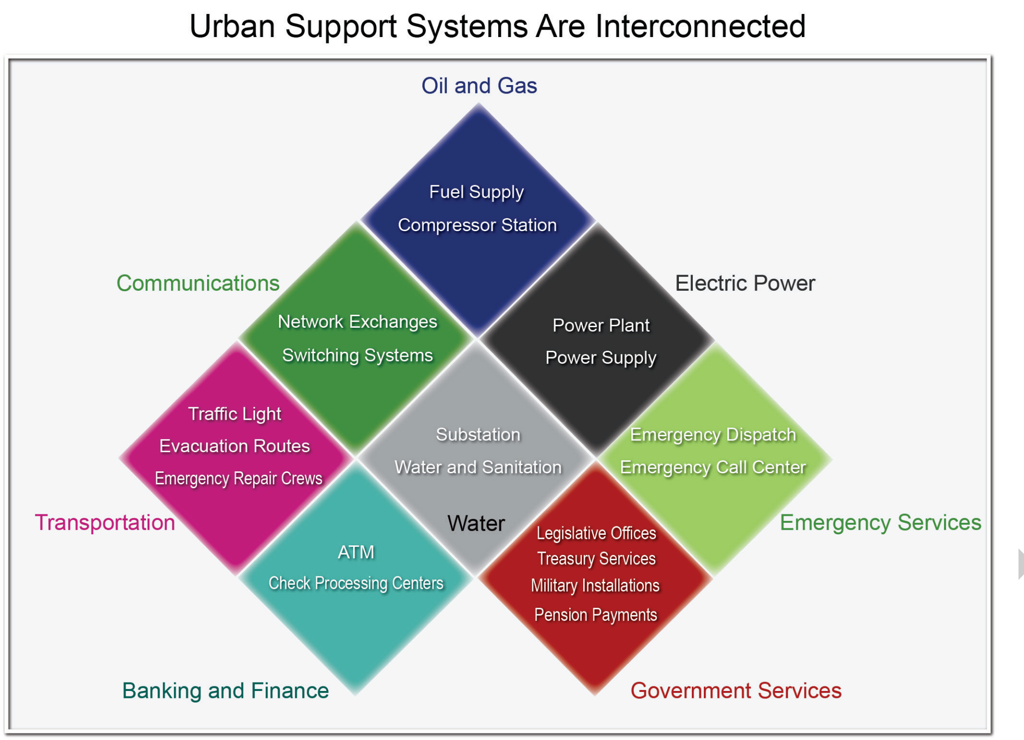

Figure 11.2: Urban Support Systems are Interconnected

Caption: In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other systems. When power supplies that serve urban areas are interrupted after a major weather event, for example, public health systems, transportation systems, and banking systems may all be affected. Schematic drawing illustrates some of these connections. (Source: DOE 2012)

Experiences in the past decade have shown that such interdependencies can lead to cascading disruptions through urban infrastructures. These disruptions, in turn, can result in unexpected impacts on communication, water, and public health sectors, at least in the short term. On August 8, 2007, New York City experienced an intense rainfall and thunderstorm event during the morning commute. Between 1.4 and 3.5 inches of rain fell within two hours (MTA 2007). The event started a cascade of transit system failures that would eventually strand 2.5 million riders, shut down much of the subway system, and severely disrupt the city's bus system (MTA 2007; Zimmerman and Faris 2010). The storm's impact was unprecedented and, coupled with two other major system disruptions that occurred in 2004 and 2007, became the impetus for a full-scale assessment and review of transit procedures and policy in response to climate change (MTA 2007, 2009; Zimmerman and Faris 2010).

In August 2003, an electric power blackout that caused 50 million people in the U.S. Northeast and Midwest and Ontario, Canada, to lose electric power further illustrates the interdependencies of major infrastructure systems. The blackout caused significant indirect damage, such as shutdowns of water treatment plants and pumping stations. Other impacts included interruptions in communication systems for air travel and control systems for oil refineries. At a more local level, the lack of air conditioning and elevator access meant many urban residents were stranded in their over-heating high-rise apartments. Similar cascading impacts have been observed from extreme weather events such as Hurricanes Katrina and Irene (Wilbanks et al. 2012). In fact, as urban infrastructures evolve to higher degrees of interconnected complexity, the likelihood of large-scale cascading impacts will increase as risks to infrastructure increase (Ellis et al. 1997).

Box: Hurricane Sandy: Urban Systems, Infrastructure, and Vulnerability

Hurricane Sandy made landfall on the New Jersey shore just south of Atlantic City on October 28, 2012 and became one of the most damaging storms to strike the continental U.S. Sandy affected cities throughout the Atlantic seaboard, extending across the eastern U.S. to Chicago, Illinois where it generated 20-foot waves on Lake Michigan and flooded the city's Lake Shore Drive. The storm's strength and resulting impact was certainly increased by the fact that the waters of the Atlantic Ocean near the coast were roughly 5˚F above normal and that the region's coastline is experiencing sea level rise as a result of a warming climate (See also Ch.2: Our Changing Climate).

Sandy caused significant loss of life as well as tremendous destruction of property and critical infrastructure. It disrupted daily life for millions of coastal zone residents across the New York-New Jersey metropolitan area, despite this being one of the best disaster-prepared coastal regions in the U.S. The death toll from Sandy in the metropolitan region exceeded 100, and the damage estimates may exceed hundreds of billions of dollars. At its peak, the storm cut electrical power to more than five million customers.

The death and injury, physical devastation, multi-day power, heat, and water outages, gasoline shortages, and cascade of collapses from Sandy's impact reveal what happens when the complex, integrated systems upon which urban life depends are stressed and fail. One example is what occurred after a Consolidated-Edison electricity distribution substation in lower Manhattan ceased operation at approximately 9 PM Monday evening, when its flood protection barrier (designed to be 1.5 feet above the 10-foot storm surge of record) was overtopped by Sandy's 14-foot storm surge. As the substation stopped functioning, it immediately caused a system-wide loss of power for more than 200,000 customers. Residents in numerous high rise apartment buildings were left without heat and lights, and also without elevator service and water (which must be pumped to upper floors).

Sandy also highlighted the vast differences in vulnerabilities across the extended metropolitan region. Communities and neighborhoods on the coast were obviously most vulnerable to the physical impact of the record storm surge. Many low-to-moderate income residents live in these areas and suffered the damage or loss of their homes, leaving tens of thousands of people displaced or homeless. As a specific sub-population, the elderly and infirm were highly vulnerable, especially those living in the coastal evacuation zone and those on upper floors of apartment buildings left without elevator service. These individuals had limited adaptive capacity because they could not easily leave their residences.

Even with the extensive devastation, the effects of the storm would have been far worse if local climate resilience strategies had not been in place. For example, the City of New York and the

Metropolitan Transportation Authority worked aggressively to protect life and property by stopping the operation of the city's subway before the storm hit and moving the train cars out of low-lying, flood-prone areas. At the height of the storm surge, all seven of the city's East River subway tunnels flooded. Catastrophic loss of life would have resulted if there had been subway trains operating in the tunnels when the storm struck. The storm also fostered vigorous debate among local and state politicians, other decision-makers, and stakeholders about how best to prepare the region for future storms – especially given the expectation that this type of event will become more frequent with ongoing climate change.

-- end box --

Social Vulnerability and Human Well-Being

Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

"Social vulnerability" describes characteristics of populations that influence their capacity to prepare for, respond to, and recover from hazards and disasters (Adger 2006; Cutter et al. 2003; Füssel 2007b; Laska and Morrow 2006). Social vulnerability also refers to the sensitivity of a population to the impacts of climate change and how different people or groups are more or less vulnerable to those impacts (Cardona et al. 2012). Those characteristics that most often influence differential impacts include socioeconomic status (wealth or poverty), age, gender, special needs, race, and ethnicity (Bates and Swan 2007; NRC 2006; Phillips et al. 2010). Further, inequalities reflecting differences in gender, age, wealth, class, ethnicity, health, and disabilities also influence coping and adaptive capacity, especially to climate change and climate-sensitive hazards (Cutter et al. 2012).

The urban elderly are particularly sensitive to heat waves. They are often physically frail, have limited financial resources, and live in relative isolation in their apartments. They may not have adequate cooling (or heating), or may be unable to temporarily locate to cooling stations. This combination led to a significant number of elderly deaths during the 1995 Chicago heat wave (Klinenberg 2003). The impacts of Hurricane Katrina in New Orleans illustrated profound differences based on race, gender, and class where these social inequalities strongly influenced the capacity of residents to prepare for and respond to the events (Brinkley 2007; Horne 2008; Weber and Peek 2012). It is difficult to assess the specific nature of vulnerability for sub-populations. Urban areas are not homogeneous in terms of their social structures that influence inequalities. Also the nature of the vulnerability is context specific, with both temporal and geographic determinants, and these also vary between and within urban areas.

Trends in Urban Adaptation – Lessons from Early Adopters

City government agencies and organizations have started urban adaptation efforts that focus on infrastructure systems and public health. However, these efforts face many barriers to implementing and incorporating wider governmental, general public, and private efforts.

City preparation efforts for climate change include planning for ways in which the infrastructure systems and buildings, ecosystem and municipal services, and residents will be affected. In the first large-scale analysis of U.S. cities, a 2011 survey showed that 58% of respondents are moving forward on climate adaptation, defined as any activity to address impacts that climate change could have on a community. Cities are engaged in activities ranging from assessment to planning to implementation, with 48% reporting that they are in the preliminary planning and discussion phases (Carmin et al. 2012).

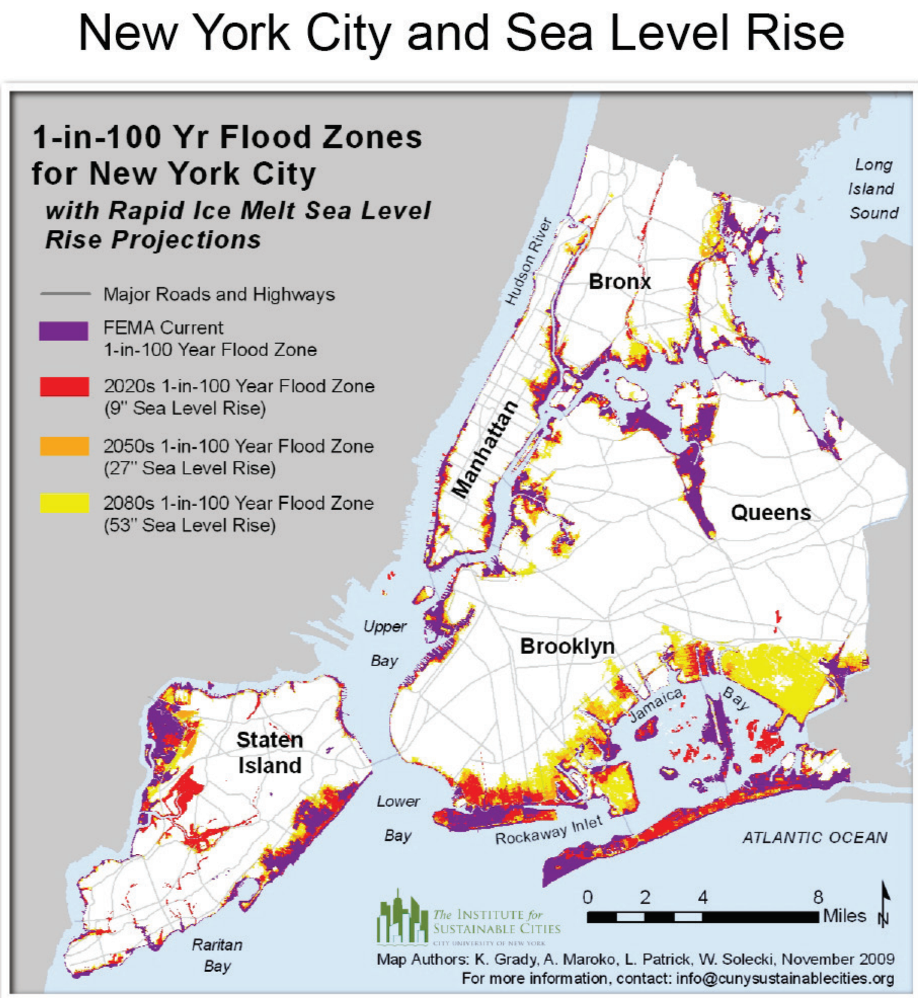

Figure 11.3: New York City and Sea Level Rise

Caption: Map shows areas in New York's five boroughs that are projected to face increased flooding over the next 70 years, assuming an increased rate of sea level rise from the past century's average. As sea level rises, storm surges reach further inland. Map does not represent precise flood boundaries, but illustrates projected increases in areas flooded under various sea level rise scenarios.

Cities either develop separate strategic adaptation plans (Carmin et al. 2012; Zimmerman and Faris 2011) or integrate adaptation into community or general plans (as have Seattle, Portland, Berkeley, and Homer, Alaska) (Solecki and Rosenzweig 2012). Cities develop or integrate adaptation into climate action plans targeted at certain sectors (like critical infrastructure) (City of Santa Cruz 2012; Cooney 2011; Füssel 2007a, 2007b; Maibach et al. 2008), and these have been effective in diverse contexts ranging from hazard mitigation and public-health planning to coastal-zone management and economic development. Climate adaptation planning requires both intra- and inter-governmental agency and department coordination (see Box on "New York City Climate Action"). As a result, many cities focus on sharing information and examining what aspects of government operations will be affected by climate change impacts in order to gain support from municipal agency stakeholders and other local officials (Moser and Ekstrom 2011). Cities also have shared climate change action experiences with other cities, both within the U.S. and internationally, as is the case with ongoing communication between decision-makers in New York City and London, England.

National, state, and local policies play an important role in fostering and sustaining adaptation. There are no national regulations specifically designed to promote urban adaptation. However, existing federal policies, like the National Environmental Protection Act, can provide incentives for adaptation strategies for managing federal property in urban areas (DOI 2011; Solecki and Rosenzweig 2012; U.S. Fish and Wildlife Service 2010). Policies and planning measures at the local level, such as building codes, zoning regulations, land-use plans, water supply management, green infrastructure initiatives, health care planning, and disaster mitigation efforts, can support adaptation (Dodman and Satterthwaite 2008; Solecki and Rosenzweig 2012; Wilbanks et al. 2012).

Engaging the public in adaptation planning and implementation has helped to inform and educate the community at large about climate change, while ensuring that information and ideas flow back to policymakers (Carmin et al. 2011; Van Aalst et al. 2008). Engagement also can help in identifying vulnerable populations (Foster et al. 2011) and in mobilizing people to encourage policy changes and take individual actions to reduce and adapt to climate change (Moser 2009). For instance, the Cambridge Climate Emergency Congress selected a demographically diverse group of resident delegates and engaged them in a deliberative process intended to express preferences and generate recommendations to inform climate action (City of Cambridge 2010; Fishkin 1991). In addition, the Boston Climate Action Leadership Committee was initiated by the Mayor's office with the expectation that they would rely on public consultation to develop recommendations for updating the city's climate action plan (City of Boston 2010, 2011).

There are many barriers to action at the city level. Adaptation requires that anticipated climate changes and impacts are evaluated and addressed in the course of the planning process (Hallegatte and Corfee-Morlot 2011; Howard and Monbiot 2009; Ch. 26: Decision Support). This means that climate or assessment data must be available, but most U.S. cities are unable to access suitable data or perform desired analyses (CCATF 2011). To address technical aspects of adaptation, cities are promoting cooperation with local experts, such the New York City Panel on Climate Change, which brings together experts from academia and the public and private sectors to consider how the region's critical infrastructure will be affected by, and can be protected from, future climate change (Rosenzweig and Solecki 2010; Rosenzweig et al. 2011). A further illustration comes from Chicago, where multi-departmental groups are focusing on specific areas identified in Chicago's Climate Action Plan (2010).

Box: New York City Climate Action

New York City leaders recognized that climate change represented a serious threat to critical infrastructure and responded with a comprehensive program to address climate change impacts and increase resilience (Solecki and Rosenzweig 2012; Wilbanks et al. 2012). The 2010 "Climate Change Adaptation in New York City: Building a Risk Management Response" report was prepared by the New York City Panel on Climate Change as a part of PlaNYC, the City's long-term sustainability plan (NPCC 2010). Major components of the process and program include:

- Multiple participatory processes, including obtaining broad public input through PlaNYC and establishment of a Climate Change Adaptation Task Force that included private and public stakeholders (NRC 2010a);
- Formation of an expert technical advisory body, the New York City Panel on Climate Change (NPCC), to support the Task Force;
- Development of a Climate Change Assessment and Action Plan that helps improve responses to present-day climate variability as well as projected future conditions;
- Defined "Climate Protection Levels" to address the effectiveness of current regulations and design standards to respond to climate change impacts; and
- Produced adaptation assessment guidelines that recognize the need for flexibility to reassess and adjust strategies over time. The guidelines include a risk matrix and prioritization framework intended to become integral parts of ongoing risk management and agency operations.

-- end box --

Private sector involvement can be influential in promoting city-level adaptation, yet to date there are limited examples of such involvement. Instances where cooperation has taken place include property insurance companies (NRC 2010a; Solecki and Rosenzweig 2012), and engineering firms that provide consulting services to cities. For example, firms providing infrastructure system plans have begun to account for projected changes in precipitation in their projects (van der Tak et al. 2010). With city and regional infrastructure systems, recent attention has focused on the potential role of private sector-generated smart technologies to advance early warning of extreme precipitation and heat waves, as well as establishing information systems that can inform local decision-makers about the status and efficiency of infrastructure (IBM News Room 2009; NRC 2010a).

Uncertainty in both the climate system and modeling techniques often is viewed as a barrier to adaptation action (Corfee-Morlot et al. 2011; Mastrandrea et al. 2010). Urban and infrastructure managers, however, recognize that uncertainty values will continue to be refined (Foster et al. 2011), and that an incremental and flexible approach to planning that draws on both structural and nonstructural measures is prudent (Carmin and Dodman 2012; NRC 2010a; Rosenzweig et al. 2010). Gaining the commitment and support of local elected officials for adaptation planning and implementation is another important challenge (Carmin et al. 2012). A compounding problem is that cities and city administrators face a wide range of other stressors demanding their attention, and have limited financial resources (NRC 2010a; see Box on "Advancing Climate Adaptation in a Metropolitan Region") .

Box: Advancing Climate Adaptation in a Metropolitan Region

A major challenge of adaptation planning and practice is coordinating efforts across many jurisdictional boundaries in extended metropolitan regions and associated regional systems. Regional government institutions may be well-suited to address this challenge, as they cover a larger geographic scope than individual cities, and have potential to coordinate the efforts of multiple jurisdictions (Solecki and Rosenzweig 2012). California already requires metropolitan planning organizations to prepare Sustainable Communities Strategies (SCS) as part of the Regional Transportation Plan process (California Senate 2008). While its focus is on reducing emissions, SCS plans prepared to date have also introduced topics related to climate change impacts and adaptation (SACOG 2012; SANDAG 2011; SCAG 2012). Examples of climate change vulnerabilities that could benefit from a regional perspective include water shortages, transportation infrastructure maintenance, loss of native plant and animal species, and energy demand.

-- end box --

Integrating climate change action in everyday city and infrastructure operations and governance (referred to as "mainstreaming") is an important planning and implementation tool for advancing adaptation in cities (NRC 2010a; Rosenzweig et al. 2010). By integrating climate-change considerations into daily operations, these efforts can forestall the need to develop a new and isolated set of climate-change specific policies or procedures (Foster et al. 2011). This strategy enables cities and other government agencies to take advantage of existing funding sources and programs, and achieve co-benefits in areas such as sustainability, public health, economic development, disaster preparedness, and environmental justice. Pursuing low-cost, no-regrets options is a particularly attractive short-term strategy for many cities (Foster et al. 2011; NRC 2010a).

Over the long term, responses to severe climate change impacts, such as sea level rise and greater frequency and intensity of other climate-related hazards, are of a scale and complexity that will likely require major expenditures and structural changes (NRC 2010a; Solecki and Rosenzweig 2012), especially in urban areas. When major infrastructure decisions must be made in order to protect human lives and urban assets, cities need access to the best available science, decision support tools, funding, and guidance. The federal government is seen by local officials to have an important role here by providing adaptation leadership and financial and technical resources, and by conducting and disseminating research (CCATF 2011; Foster et al. 2011; NRC 2010a).

Traceable Accounts

Chapter 11: Urban Systems, Infrastructure, and Vulnerability

Key Message Process: In developing key messages, the report author team engaged in multiple technical discussions via teleconference. A consensus process was used to determine the final set of key messages which support extensive evidence documented in two Technical Report Inputs to the U.S. National Climate Assessment on urban systems, infrastructure, and vulnerability: (Wilbanks et al. 2012) Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report For The U.S. Department of Energy in Support of the National Climate Assessment, and (Solecki and Rosenzweig (2012) U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues). Other Technical Input reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Key message #1/4	**Climate change and its impacts threaten the well-being of urban residents in all regions of the U.S. Essential local and regional infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts.**
Description of evidence base	Recent studies have reported that population and economic growth have made urban environments more fragile and deficient (Solecki and Rosenzweig 2012; Wilbanks et al. 2012), with work projecting increased stresses due to climate change (McCrea et al. 2011) and increased costs of adaptation plans due to urban development (Burchell et al. 2002). Additionally, a few publications have assessed the main drivers of vulnerability (Depietri et al. 2012; Douglas et al. 2011; Emrich and Cutter 2011) and the effects of the amalgamation of climate-change stresses with other urban and infrastructure stressors (Solecki and Rosenzweig 2012)
New information and remaining uncertainties	Since population trends and infrastructure assessments are well established and documented, the largest uncertainties are associated with the rate and extent of potential climate change Current publications have explored the driving factors of vulnerability in urban systems (Depietri et al. 2012; Douglas et al. 2011; Emrich and Cutter 2011) and the effects of the combined effect of climate-change and existing urban stressors (Solecki and Rosenzweig 2012).
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **Very High** that climate change and its impacts threaten the well-being of urban residents in all regions of the U.S. Given the evidence base and remaining uncertainties, confidence is **Very High** that essential local and regional infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 11: Urban Systems, Infrastructure, and Vulnerability

Key Message Process: See key message #1.

Key message #2/4	**In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.**
Description of evidence base	The interconnections between urban systems and infrastructures have been noted in the past (Ellis et al. 1997), with recent work expanding on this principal to assess the risk this interconnectivity poses. Kirshen et al. (2008) explored the misconception of independent systems and stressed their interactive and interdependent nature. Seto et al. (2012) explored how the effects of climate change on one system ultimately affect systems that are dependent upon it. Wilbank et al. (2012) looked at economic effects from climate change and how they will affect urban areas. Noted examples of this interconnectivity can be found in a number of publications concerning hurricane Katrina (Myers et al. 2008), intense weather in New York City (MTA 2007; Zimmerman and Faris 2010), and the vulnerability of U.S. oil refineries and electric power plants (Wilbanks et al. 2012; Zimmerman 2006).
New information and remaining uncertainties	The extensive number of infrastructure assessments has resulted in well-documented system interdependencies and cascade effects. Therefore, the most significant uncertainties are associated with the rate and extent of potential climate change. Recent work has delved deeper into the interconnectivity of urban systems and infrastructure (Seto et al. 2012; Wilbanks et al. 2012) and has expressed the importance understanding these interactions when adapting to climate change.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **Very High** that in urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 11: Urban Systems, Infrastructure, and Vulnerability

Key Message Process: See key message #1.

Key message #3/4	**Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.**
Description of evidence base	The topic of social vulnerability has been extensively studied (Adger 2006; Cutter et al. 2003; Füssel 2007b; Laska and Morrow 2006), with some work detailing the social characteristics that are the most influential (Bates and Swan 2007; NRC 2006; Phillips et al. 2010) . More recent work has addressed the vulnerability of populations to climate change (Cardona et al. 2012) and how social inequalities influence the adaptive capacity to climate change (Cutter et al. 2012). Some empirical studies of U.S. urban areas were explored concerning these issues (Emrich and Cutter 2011).
New information and remaining uncertainties	Since population trends and socio-economic factors associated with vulnerability and adaptive capacity are well established and documented, the largest uncertainties are associated with the rate and extent of potential climate change. Recent work has addressed the social vulnerabilities to climate change at a more detailed level than in the past (Cardona et al. 2012; Cutter et al. 2003), which informs of the constraints they can have to climate change adaptation.
Assessment of confidence based on evidence	Given the evidence base and remaining uncertainties, confidence is **Very High** that the climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

1 **Chapter 11: Urban Systems, Infrastructure, and Vulnerability**

2 **Key Message Process:** See key message #1.

Key message #4/4	**City government agencies and organizations have started urban adaptation efforts that focus on infrastructure systems and public health. However, these efforts face many barriers to implementing and incorporating wider governmental, general public, and private efforts.**
Description of evidence base	Urban adaptation is already underway with a number of cities developing plans at the city (Carmin et al. 2012; City of Santa Cruz 2012; Cooney 2011; Füssel 2007b; Maibach et al. 2008; Zimmerman and Faris 2011) and state levels (Carmin et al. 2012), with some integrating adaptation into communities (Solecki and Rosenzweig 2012) and sharing information and assessing potential impacts (Moser and Ekstrom 2011). Some recent publications have explored how incentives and support can benefit climate adaptation through policy planning at local level (Dodman and Satterthwaite 2008; Solecki and Rosenzweig 2012; Wilbanks et al. 2012) and engaging the public (Carmin et al. 2011; Foster et al. 2011; Moser 2009; Van Aalst et al. 2008). Studies have shown that some barriers exist that can hinder the adaptation process, which has been demonstrated through publications assessing the availability of scientific data (Carmin et al. 2012; CCATF 2011) that is integral to the evaluation and planning process (Hallegatte and Corfee-Morlot 2011; Howard and Monbiot 2009), uncertainty in the climate system and modeling techniques (Corfee-Morlot et al. 2011; Mastrandrea et al. 2010), and gaining support and commitment from local officials (Carmin et al. 2012; NRC 2010a).
New information and remaining uncertainties	Besides uncertainties associated with the rate and extent of potential climate change, uncertainties emerge from the fact that to-date, there have been few extended case studies examining how U.S. cities are responding to climate change (<10 studies). Furthermore, only one large-scale survey of U.S. cites has been conducted for which results have been published and widely available.
Assessment of confidence based on evidence	Given the evidence base, confidence is **Very High** that city government agencies and organizations have started urban adaptation efforts that focus on infrastructure systems and public health.

3

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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12. Impacts of Climate Change on Tribal, Indigenous, and Native Lands and Resources

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Key Messages

1. **Climate change related impacts, such as increased frequency and intensity of wildfires, higher temperatures, ecosystem changes, ocean acidification, forest loss, and habitat damage, are threatening Native American and Alaska Native access to traditional foods such as salmon, shellfish, wild and cultivated crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.**
2. **A significant decrease in water quality and quantity caused by a variety of factors including climate change, is affecting Native Americans' and Alaska Natives' drinking water supplies, food, cultures, ceremonies, and traditional ways of life. Native communities' vulnerabilities and lack of capacity to adapt to climate change are exacerbated by land-use policies, political marginalization, legal issues associated with tribal water rights, and poor socioeconomic conditions.**
3. **Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and/or loss of homes and settlements, food insecurity from changing availability of wild food sources, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.**
4. **Alaska Native communities are increasingly exposed to health and livelihood hazards from permafrost thawing and increasing temperatures, which are causing damage to roads, water supply and sanitation systems, homes, schools, ice cellars, and ice roads, and threatening traditional lifestyles.**
5. **Accelerated sea level rise, erosion, permafrost thaw, and/or increased intensity of weather events are forcing relocation of entire tribal and indigenous communities in Alaska, Louisiana, the Pacific Islands, and other coastal locations. These relocations and the lack of governance mechanisms or funding to support them are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.**

We humbly ask permission from all our relatives;
our elders, our families, our children, the winged and the insects, the four-legged, the swimmers
and all the plant and animal nations, to speak. Our Mother has cried out to us. She is in pain.
We are called to answer her cries. Msit No'Kmaq – All my relations!

Introduction

The peoples, lands, and resources of indigenous communities in the United States, Including Alaska and the Pacific Rim, face an array of climate change impacts and vulnerabilities that threaten many Native communities. The consequences of observed and projected climate change have and will undermine indigenous ways of life that have persisted for thousands of years. Key vulnerabilities include: the loss of traditional knowledge, forests and ecosystems, food security and traditional foods, and water; Arctic sea ice loss; permafrost thaw; and relocation from historic homelands.

Tribal Populations Extend Beyond Reservation Lands

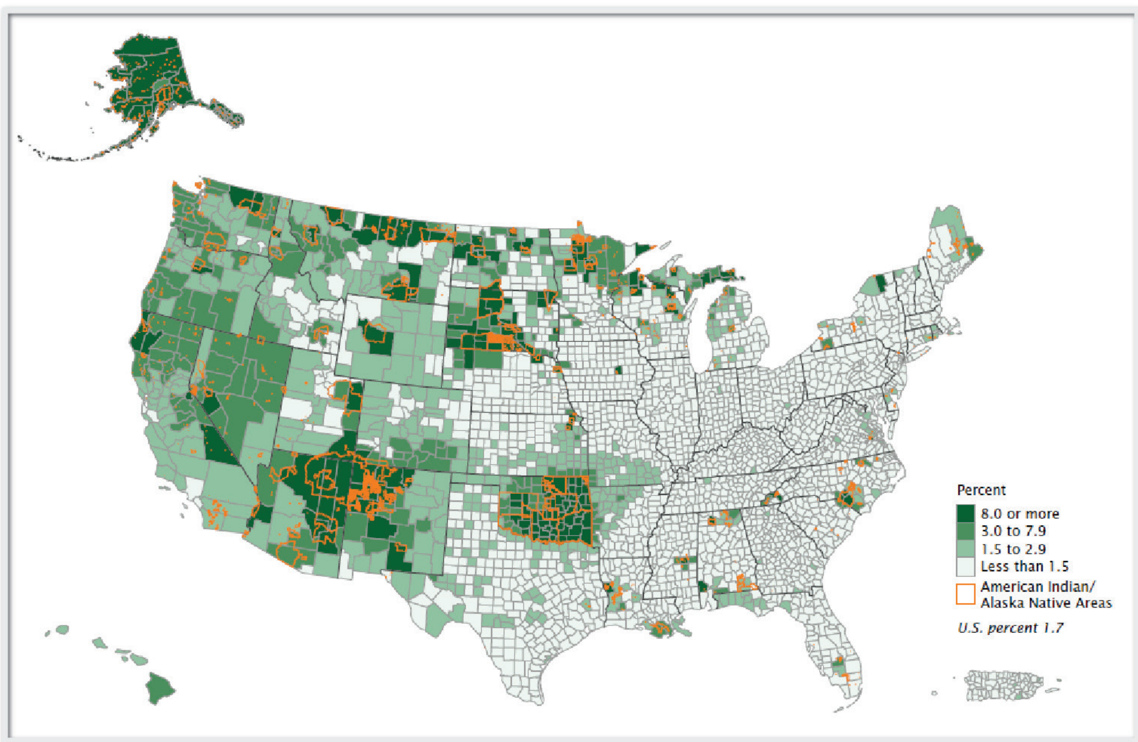

Figure 12.1: Tribal Populations Extend beyond Reservation Lands

Caption: Census data shows that American Indian and Alaska Native populations are concentrated around but are not limited to reservation lands, like the Hopi and Navajo in Arizona and New Mexico, the Choctaw, Chicasaw, and Cherokee in Oklahoma, and various Sioux tribes in the Dakotas and Montana (Source: U.S. Census Bureau 2010). Not depicted in this graphic is the proportion of Native Americans who live in and around urban centers (such as Chicago, Minneapolis, Denver, Albuquerque, Phoenix, San

Francisco, and Los Angeles) yet still maintain strong family ties to their tribes and tribal lands.

Climate change impacts on the 566 federally recognized tribes and other Indigenous groups in the U.S., including state-recognized and non-federally recognized tribes, are projected to be especially severe. Many Native populations are already challenged by adverse socioeconomic factors, such as extreme poverty and substandard housing, lack of health and community services, food, infrastructure, transportation, education, and employment, plus the high cost of fuel (AIHEC 2006; Honor the Earth 2002; Maynard 2002). Native populations are also vulnerable because of their close relationships with the environment for their physical, mental, intellectual, social, and cultural well-being. In addition, as the risk of intense natural disasters and temperature extremes increases, Native communities are vulnerable because they already face a severe housing shortage, lacking approximately half a million safe, healthy, and affordable homes (NTGBC 2011).

Many Tribes, Many Climate Change Initiatives

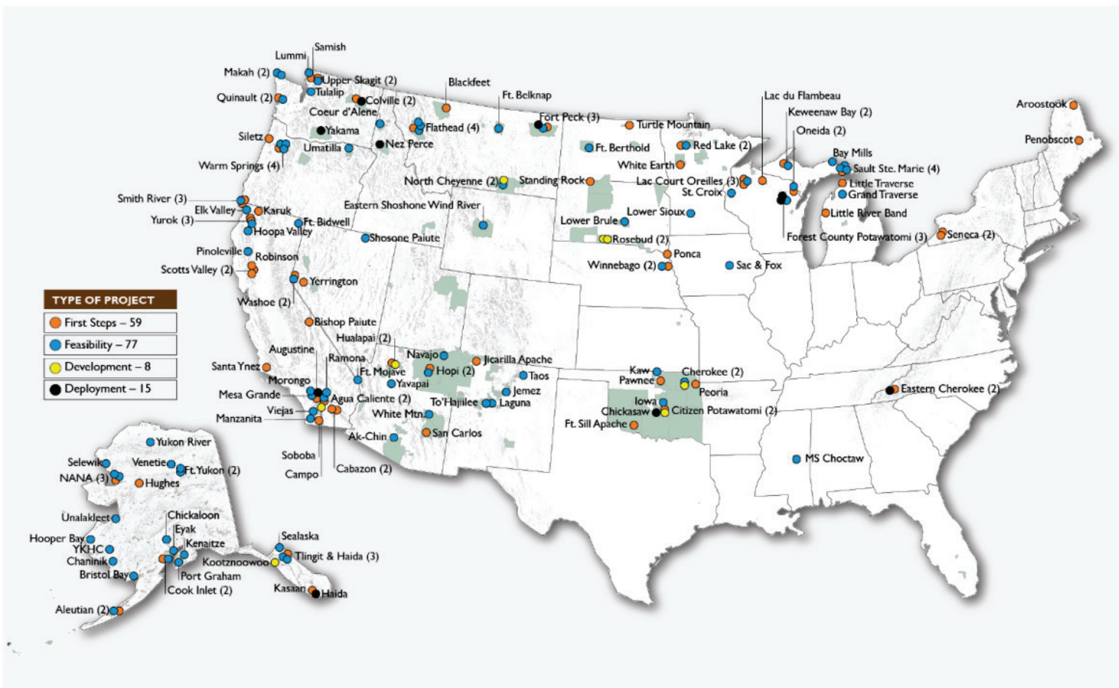

Figure 12.2: Many Tribes, Many Climate Change Initiatives

Caption: From developing biomass energy projects on the Quinault Indian Nation in Washington to energy efficiency improvement efforts on the Cherokee Indian Reservation in North Carolina, tribes are investigating ways to mitigate and adapt to climate changes. The map shows initiatives by federally recognized tribes only. (Source: DOE 2011)

Of the 5.2 million American Indians and Alaska Natives registered in the U.S. census, approximately 1.1 million live on or near reservations or Native lands, located mostly in the Northwest, Southwest, Great Plains, and Alaska. Tribal lands include approximately 56 million acres (about 3% of U.S. lands) in the 48 contiguous states and 44 million acres held by Alaska Native corporations (U.S. Census Bureau 2010). Most reservations are small and often remote or isolated, with a few larger exceptions such as the Navajo Reservation in Arizona, Utah, and New Mexico, which supports 175,000 residents (U.S. Census Bureau 2010).

Native American, Alaska Native, and other indigenous communities across the U.S. share unique historical and cultural relationships with tribal or ancestral lands. Some climate change adaptation opportunities exist on Native lands, and traditional knowledge can enhance adaptation and sustainability strategies. In many cases, however, adaptation options are limited by poverty, lack of resources, or, for some Native communities, such as those along the northern coast of Alaska or certain low-lying Pacific Islands, because there may be no land left to call their own.

Climate Change and Traditional Knowledge

Indigenous traditional knowledge has emerged in national and international arenas as a source of rich information for indigenous and non-indigenous climate assessments, policies, and adaptation strategies. Working Group II of the Intergovernmental Panel on Climate Change Fourth Assessment Report recognized traditional knowledge as an important information source for improving the understanding of climate change and other changes over time and for developing comprehensive natural resource management and climate adaptation strategies (Anisimov et al. 2007).

Traditional knowledge is essential to the economic and cultural survival of indigenous peoples, and, arguably, cultures throughout the world. Traditional knowledge has been defined as “a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment” (Berkes 1993, 2008). From an indigenous perspective, traditional knowledge encompasses all that is known about the world around us and how to apply that knowledge in relation to those beings that share the world. As the elders of these communities – the “knowledge keepers” – pass away, the continued existence and viability of traditional knowledge is threatened. It is important to preserve the diverse traditional teachings and employ them to strive for balance among the physical, the spiritual, emotional, and intellectual – all things that encompass “wolakota”, meaning to be a complete human being (A. White-Hat Sr. 2012, personal communication).

Merideth et al. (1998) suggest that many, if not all, indigenous resource managers believe their cultures already possess sufficient knowledge to respond to climate variation and change. However, there are elements of traditional knowledge that are identified as being increasingly vulnerable with changing climatic conditions. These elements include language, culture and cultural identities, ceremonies, sense of place, all our relations (human and non-human), and traditional ways of life. The use of indigenous and traditional knowledge to solve climate change issues in Indian country has been called “indigenuity” – indigenous knowledge plus ingenuity (Wildcat 2009).

Native cultures are directly tied to Native places and homelands, reflecting the indigenous perspective that includes the "power of place" (Deloria and Wildcat 2001). Many indigenous peoples regard all people, plants, and animals that share our world as relatives, not resources. Language, ceremonies, cultures, practices, and food sources evolved in places. The wisdom and knowledge of Native people resides in songs, dances, art, language, and music. By regarding all things as relatives, not resources, natural laws dictate that people care for their relatives in responsible ways. *"When you say, 'my mother is in pain,' it's very different from saying 'the earth is experiencing climate change'"* (A. White-Hat Sr. 2012, personal communication; Papalii Failautusi Avegalio 2012, personal communication; Souza and Tanimoto 2012). As climate change increasingly threatens Native places, cultural identities, and practices, indigenous relationships with all relations are similarly threatened.

Traditional knowledge has developed tangible and reliable methods for recording historic weather and climate variability and their impacts on native societies (Therrell and Trotter 2011). For example, tribal community historians (winter count keepers) on the northern Great Plains maintained and used pictographs recorded on buffalo hides to remember the sequence of events that marked each year, dating back to the 1600s. These once-reliable methods are becoming increasingly more difficult to maintain and less reliable as time passes (Nickels et al. 2006).

There are recent examples, however, where traditional knowledge and western-based approaches are used together to address climate change and related impacts. For example, the Alaska Native Tribal Health Consortium chronicles climate change impacts on the landscape and on human health, and also develops adaptation strategies. This Consortium employs western science, traditional ecological knowledge, and a vast network of "Local Environmental Observers" to develop comprehensive, community-scaled climate change health assessments (ANTHC 2012). During a recent drought on the Navajo Reservation, traditional knowledge and western approaches were also applied together, as researchers worked with Navajo elders to observe metrological and hydrological changes and other phenomena in an effort to assess and reduce disaster risks (Redsteer et al. 2011).

Forests, Fires, and Food

Climate change related impacts, such as increased frequency and intensity of wildfires, higher temperatures, ecosystem changes, ocean acidification, forest loss, and habitat damage, are threatening Native American and Alaska Native access to traditional foods such as salmon, shellfish, wild and cultivated crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.

The impacts of climate change on forests and ecosystems are expected to have direct effects on culturally important plant and animal species, which will affect tribal sovereignty, culture, and economies. Observed impacts include species loss and shifts in species range (Louisiana Workshop 2012; Swinomish Indian Tribal Community 2010), including northward migration of the boreal forest and changes in the distribution and density of wildlife species (Trainor et al. 2009). Loss of biodiversity, impacts on culturally important native plants and animals, increases in invasive species, bark beetle damage to forests, and increased risk of forest fires have been observed in the Southwest (ITEP 2011), across much of the West, and in Alaska (Ch. 7: Forestry; Ch. 8: Ecosystems and Biodiversity).

Rising temperatures and hotter drier summers are projected to increase the frequency and intensity of large wildfires (Ch. 20: Southwest; Ch. 2: Our Changing Climate). Warmer, drier, and longer fire seasons and increased forest fuel load will lead to insect outbreaks and the spread of invasive species, dry grasses, and other fuel sources (IPCC 2007; NWF 2011). Wildfire threatens Native and tribal homes, safety, economies, culturally important species, medicinal plants, traditional foods, and cultural sites. *"Fire affects the plants, which affect the water, which affects the fish, which affect terrestrial plants and animals, all of which the Karuk rely on for cultural perpetuity"* (Karuk Tribe 2010).

In interior Alaska, rural Native communities are experiencing new risks associated with climate-induced wildfires in boreal forests and Arctic tundra (Higuera et al. 2008; Mack et al. 2011. See also Ch. 22: Alaska and Arctic). Reliance on local, wild foods and the isolated nature of these communities, coupled with their varied preparedness and limited ability to deal with wildfires, leaves many communities at an increased risk of devastation brought on by cataclysmic fires. While efforts are being made to better coordinate rural responses to wildfires in Alaska, current responses are limited by organization and geographic community isolation (Trainor et al. 2009).

Indigenous peoples have historically depended on a wide variety of local plant and animal species for food (frequently referred to as traditional foods), medicines, ceremonies, community, and economic health for countless generations. These include corn, beans, squash, seals, fish, shellfish, bison, bear, caribou, walrus, moose, deer, wild rice, cottonwood trees, and a multitude of native flora and fauna (ITEP 2010, 2011; Louisiana Workshop 2012; Minnesota Department of Natural Resources 2008; Redsteer et al. 2011a; Riley et al. 2012; Swinomish Indian Tribal Community 2010; Verbrugge 2010). A changing climate affects the availability, tribal access to, and health of these resources (CPR 2011; Guyot et al. 2006; Kaufman 2011; Swinomish Indian Tribal Community 2010; University of Oregon 2011a; Verbrugge 2010). This in turn threatens tribal customs, cultures, and identity.

Medicinal and food plants are becoming increasingly difficult to find or are no longer occurring in historic ranges (Riley et al. 2012). Subsequent shifts from traditional lifestyles and diet, compounded by persistent poverty, food insecurity, the cost of non-traditional foods, and poor housing conditions have led to increasing health problems in communities, thus increasing the risk to food and resource security. Climate change is likely to amplify other indirect effects to traditional foods and resources, including limited access to gathering places and hunting grounds, and environmental pollution (CPR 2011; Kaufman 2011; University of Oregon 2011a; Verbrugge 2010).

Water Quality and Quantity

A significant decrease in water quality and quantity, caused by a variety of factors including climate change, is affecting Native Americans' and Alaska Natives' drinking water supplies, food, cultures, ceremonies, and traditional ways of life. Native communities' vulnerabilities and lack of capacity to adapt to climate change are exacerbated by land-use policies, political marginalization, legal issues associated with tribal water rights, and poor socioeconomic conditions.

Native communities and tribes in different parts of the U.S. have observed changes in precipitation affecting their water resources. On the Colorado Plateau, tribes have been experiencing drought for more than a decade (Ferguson and Crimmins 2009; Garfin et al. 2012). Navajo elders have observed long-term decreases in annual snowfall over the past century, a transition from wet to dry conditions in the 1940s, and a decline in surface water features (Hiza et al. 2011). Southwest tribes have observed impacts on their agriculture and livestock, the loss of springs and medicinal and culturally important plants and animals, and impacts on drinking water supplies (Christensen 2003; Ferguson and Crimmins 2009; Garfin et al. 2012). In the Northwest, tribal treaty rights to traditional territories and resources are being affected by the reduction of rainfall and snowmelt in the mountains, melting glaciers, rising temperatures, and shifts in ocean currents (McNutt 2008). In Hawai'i, Native peoples have observed a shortening of the rainy season, an increasing intensity of storms and flooding, and a rainfall pattern that has become unpredictable (Souza and Tanimoto 2012). In Alaska, water availability, quality, and quantity are threatened by the consequences of permafrost thaw, which has damaged community water infrastructure, as well as by the northward extension of diseases such as Giardia, a result of disease-carriers like beavers moving northward in response to climate warming (Brubaker et al. 2011).

U.S. Native American tribes have unique and significant adaptation needs related to climate impacts on water. There is little available data to establish baseline climatic conditions on tribal lands, and many tribes do not have sufficient capacity to monitor changing conditions (Ferguson et al. 2011). Without scientific monitoring, tribal decision-makers lack the data needed to quantify and evaluate the current conditions and emerging trends in precipitation, streamflow, and soil moisture, and to plan and manage resources accordingly (Collins et al. 2010; Garfin et al. 2012). Water infrastructure is in disrepair or lacking on some reservations (Ojima et al. 2012; Redsteer et al. 2011b). Approximately 30% of the population of the Navajo Nation is not served by municipal systems and must haul water to meet their daily needs (Navajo Nation Department of Water Resources 2011). Furthermore, there is an overall lack of financial resources to support basic water infrastructure on tribal lands (Ferguson et al. 2011). Uncertainty associated with undefined tribal water rights make it difficult to determine strategies to deal with water resource issues (Ojima et al. 2012).

Sand Dune Expansion

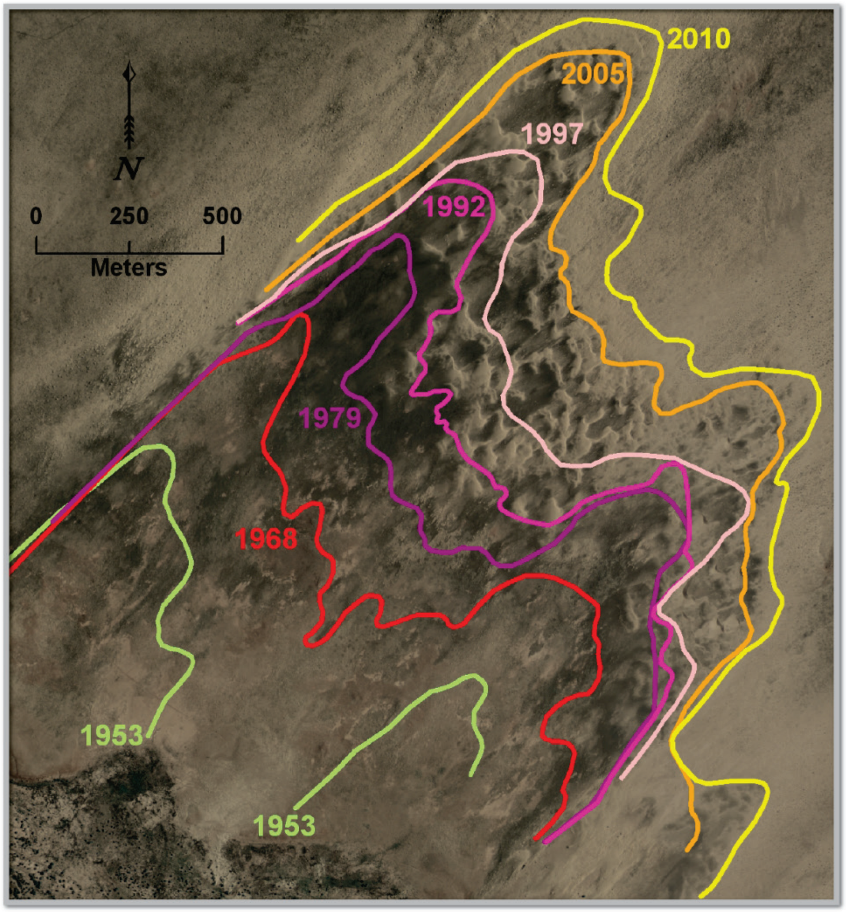

Figure 12.3: Sand Dune Expansion

Caption: On the Arizona portion of the Navajo Nation, recurring drought and rising temperatures have accelerated growth and movement of sand dunes. Map above shows range and movement of Great Falls Dune Field from 1953-2010. Moving and/or growing dunes can threaten roads, homes, traditional grazing areas, and other tribal assets. (Source: Redsteer et al. 2011a)

Declining Sea Ice

Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and/or loss of homes and settlements, food insecurity from changing availability of wild food sources, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.

"…since the late 1970s, communities along the coast of the northern Bering and Chukchi Seas have noticed substantial changes in the ocean and the animals that live there. While we are used to changes from year-to-year in weather, hunting conditions, ice patterns, and animal populations, the past two decades have seen clear trends in many environmental factors. If these trends continue, we can expect major, perhaps irreversible, impacts to our communities…."

(C. Pungowiyi 2009, personal communication)

Scientists across the Arctic have documented regional warming over the past few decades at twice the global rate, and indigenous Arctic communities have been observing the changes in their daily lives. This warming is accompanied by significant reductions in sea ice thickness and extent, increased permafrost thaw, more extreme weather and severe storms, changes in seasonal ice melt/freeze of lakes and rivers, water temperature, flooding patterns, erosion, and snowfall timing and type (Ch.2: Our Changing Climate; C. Pungowiyi 2009, personal communication; Hinzman et al. 2005; Laidler et al. 2009). These climate-driven changes in turn increase the number of serious problems for Alaska Native populations, which include: injury from extreme or unpredictable weather and thinning sea ice, which can trap people far from home; changing snow and ice conditions for predictable and safe hunting, fishing, or herding; malnutrition and food insecurity from lack of access to subsistence food; contamination of food and water; increasing economic, mental, and social problems from loss of culture and traditional livelihood; increases in infectious diseases; and loss of buildings and infrastructure from permafrost erosion and thawing, resulting in the relocation of entire communities (Brubaker et al. 2011; C. Pungowiyi 2009, personal communication; Parkinson 2009).

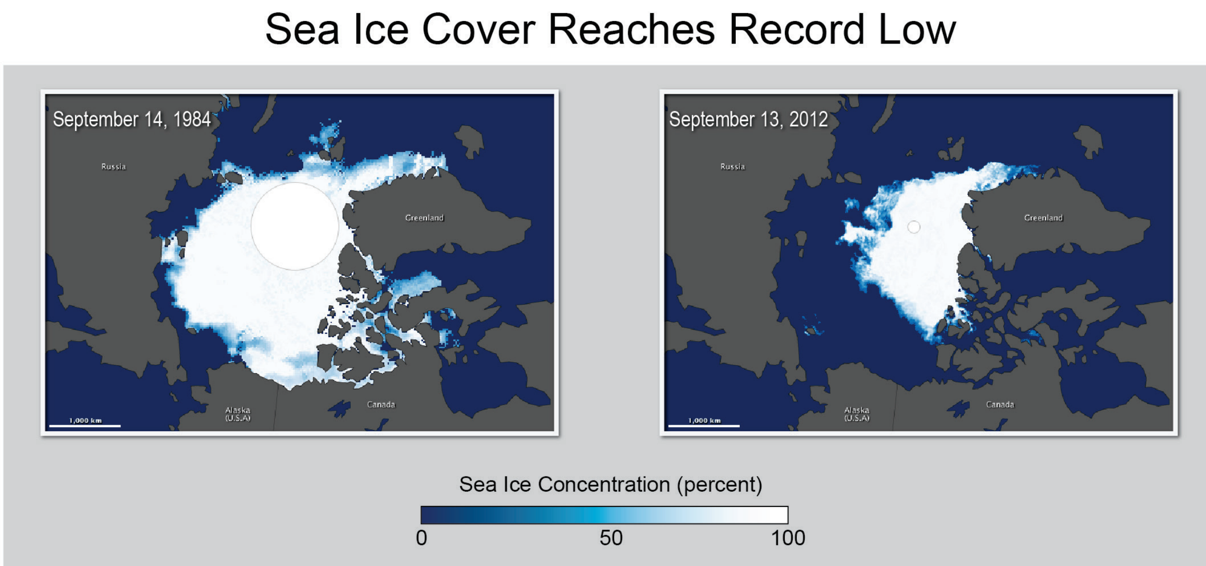

Figure 12.4: Sea Ice Cover Reaches Record Low

Caption: In August and September 2012, sea ice covered less of the Arctic Ocean than any time since at least 1979, when the first reliable satellite measurements began. The long-term retreat of sea ice has occurred faster than climate models had predicted. The average minimum extent of sea ice for 1979-2000 was 2.59 million square miles. Top image shows Arctic minimum extent from 1984, which was about the average minimum extent for 1979-2000. The image below shows that the extent of sea ice had dropped to 1.32 million square miles at the end of summer 2012. Alaska Native coastal communities rely on sea ice for many reasons, including its role as a buffer against coastal erosion from storms. Source: NASA Earth Observatory (n.d.) World of Change: Arctic Sea Ice,

http://earthobservatory.nasa.gov/Features/WorldOfChange/sea_ice.php

Alaska Native Inupiat and Yupik experts and scientists have observed stronger winds than in previous decades (C. Pungowiyi 2009, personal communication; Gearheard et al. 2010). They also observe accelerated ice and snowmelt, and movement of ice and marine mammals far beyond hunting access. The thinning sea ice, earlier ice break-up, increasing temperatures, and changes in precipitation (for example, in the timing and amount of snow) also cause changes in critical feeding, resting, breeding, and denning habitats for arctic mammals important as subsistence foods, like polar bears, walrus, and seals (C. Pungowiyi 2006, personal communication; Laidler et al. 2009).

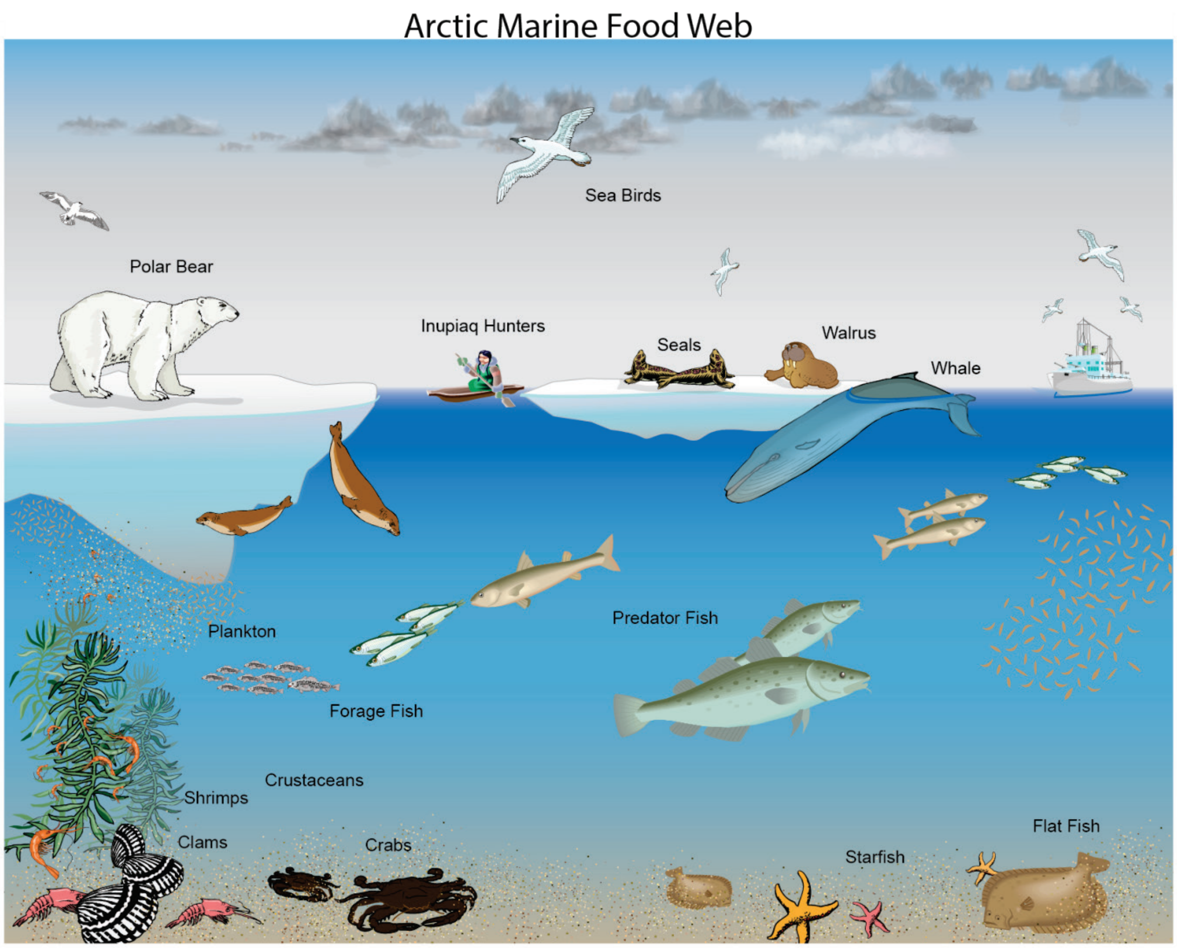

Figure 12.5: Arctic Marine Food Web

Caption: Dramatic reductions in Arctic sea ice and changes in its timing and composition affect the entire food web, including many Inupiat communities that continue to rely heavily on subsistence hunting and fishing. (Source: NOAA NCDC, 2012)

Permafrost Thaw

Alaska Native communities are increasingly exposed to health and livelihood hazards from permafrost thawing and increasing temperatures, which are causing damage to roads, water supply and sanitation systems, homes, schools, ice cellars, and ice roads, and threatening traditional lifestyles.

The increased thawing of permafrost (permanently frozen soil) along the coasts and rivers is an especially potent threat to Alaska Native villages because it causes serious erosion, flooding, and destruction of homes, buildings, and roads (Ch.22, Alaska and Arctic Chapter, Key Message 3). This loss of infrastructure is further exacerbated by loss of land-fast sea ice, sea level rise, and increasingly severe storms (McClintock 2009; University of Oregon 2011b). At this time, more than 30 Native villages in Alaska (such as Newtok and Shishmaref) are either in need of, or in the process of, relocating their entire village (Bender et al. 2011).

Serious public health issues arise due to damaged infrastructure caused by these multiple erosion threats. Among them are loss of clean water for drinking and hygiene, saltwater intrusion, and sewage contamination that could cause respiratory and gastrointestinal infections, pneumonia, and skin infections (McClintock 2009; Parkinson 2009; Parkinson and Evengård 2009). In addition, permafrost thaw is causing food insecurity in Alaska Native communities due to the thawing of ice cellars or ice houses for subsistence food storage. This in turn leads to food contamination and sickness as well as dependence upon expensive, less healthy, non-traditional "store-bought" foods (Brubaker et al. 2009; Ford and Berrang-Ford 2009; Parkinson and Evengård 2009).

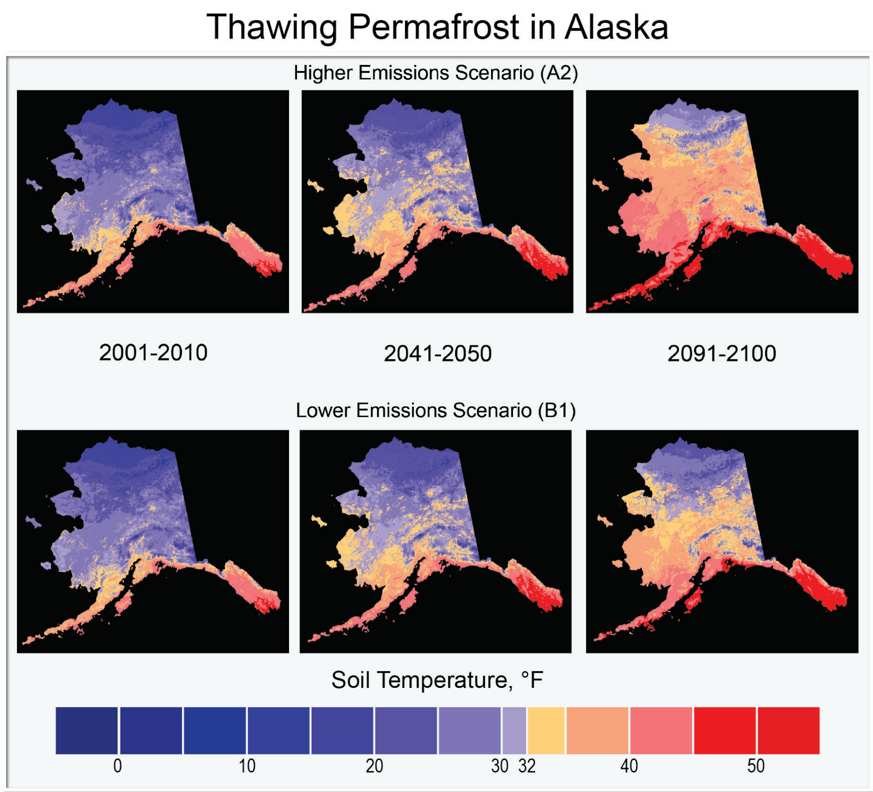

Figure 12.6: Thawing Permafrost in Alaska

Caption: The maps show projected ground temperature at a depth of about 3 feet assuming continued increases in emissions (top row, A2 scenario) and assuming a substantial reduction in emissions (bottom row, B1 scenario). Many Alaska Natives depend on permafrost for ice cellars to store frozen food, and replacing these cellars with electricity-driven freezers is expensive or otherwise infeasible. Permafrost thawing also affects infrastructure like roads and utility lines. (Source: Permafrost Lab, Geophysical Institute, University of Alaska Fairbanks, 2012)

Relocation

Accelerated sea level rise, erosion, permafrost thaw, and/or increased intensity of weather events are forcing relocation of entire tribal communities in Alaska, Louisiana, the Pacific Islands. and other coastal locations. These relocations and the lack of governance mechanisms or funding to support them are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.

Native peoples are no strangers to relocation and its consequences on their communities. Many eastern and southeastern tribal communities were forced to relocate to Canada or the western Great Lakes in the late 1700s and early 1800s and, later, to Oklahoma, compelling them to adjust and adapt to new and unfamiliar landscapes, subsistence resources, and climatic conditions. Now, Native peoples in Alaska and other parts of the coastal U.S., such as the Southeast, are facing relocation as a consequence of climate change (Bronen 2011; Louisiana Workshop 2012; Shearer 2012)

For example, Newtok, a traditional Yup'ik village in Alaska, is experiencing accelerated rates of erosion caused by the combination of decreased Arctic sea ice, thawing permafrost, and increased intensity of weather events. As a result, the community has lost critical basic necessities and infrastructure. While progress has been made toward relocation, limitations of existing federal and state statutes and regulations have impeded their efforts, and the absence of legal authority and a governance structure to facilitate relocation are significant barriers to the relocation of Newtok and other Alaska Native villages (State of Alaska Division of Community and Regional Affairs Planning and Land Management 2012). Tribal communities in coastal Louisiana are experiencing warming-induced rising sea levels, along with saltwater intrusion and intense erosion and land loss due to oil and dam development, forcing them to either relocate or try to find ways to save their land (Louisiana Workshop 2012). Native Pacific Island communities such as Tuvalu are also being forced to consider relocation plans due to increasing sea level rise and storm surges (IPCC 2007).

Currently, the U.S. lacks an institutional framework to relocate entire communities. National, state, local, and tribal government agencies lack the legal authority and the technical, organizational, and financial capacity to implement relocation processes for communities forcibly displaced by climate change. New governance institutions are needed to specifically respond to the increasing necessity for climate change-induced relocation.

"In Indigenous cultures, it is understood that ecosystems are chaotic, complex, organic, in a constant state of flux, and filled with diversity. No one part of an ecosystem is considered more important than another part and all parts have synergistic roles to play. Indigenous communities say that "all things are connected" – the land to the air and water, the earth to the sky, the plants to the animals, the people to the spirit."

Inupiat Leader – Patricia Cochran

Traceable Accounts

Chapter 12: Tribal, Indigenous, and Native Lands and Resources

Key Message Process: A central component of the assessment process was participation by members of the Chapter Author Team in a number of climate change meetings attended by indigenous peoples and other interested parties focusing on issues relevant to Tribal and Indigenous peoples. These meetings included:

Oklahoma Inter-Tribal Meeting on Climate Variability and Change held on December 12, 2011 at the National Weather Center, Norman, OK, attended by 73 people (Riley et al. 2012).

Indigenous Knowledge and Education (IKE) Hui Climate Change and Indigenous Cultures forum held in January 2012 in Hawai‘i and attended by 36 people. (Souza and Tanimoto 2012)

Alaska Forum on the Environment held from February 6-10, 2012 at the Dena’ina Convention Center in Anchorage, Alaska and attended by about 1400 people with approximately 30 to 60 people per session.

Stories of Change: Coastal Louisiana Tribal Communities’ Experiences of a Transforming Environment; Workshop held from January 22-27 in Pointe-au-Chein, Louisiana and attended by 47 people (Louisiana Workshop 2012).

American Indian Alaska Native Climate Change Working Group 2012 Spring Meeting held from April 23–24, 2012 at the Desert Diamond Hotel-Casino in Tucson, Arizona and attended by 80 people.

In developing key messages, the Chapter Author Team engaged in multiple technical discussions via teleconferences from August 2011 to March 2012 as they reviewed more than 200 technical inputs provided by the public, as well as other published literature and professional judgment. Subsequently, the chapter author team teleconferenced weekly between March and July 2012 for expert deliberations of draft key messages by the authors wherein each message was defended by the entire author team before the key message was selected for inclusion in the Chapter Report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define “key vulnerabilities.”

Key message #1/5	**Climate change related impacts, such as increased frequency and intensity of wildfires, higher temperatures, ecosystem changes, ocean acidification, forest loss, and habitat damage, are threatening Native American and Alaska Native access to traditional foods such as salmon, shellfish, wild and cultivated crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.**
Description of evidence base	The key message and supporting chapter text summarize extensive evidence documented in more than 200 technical input reports on a wide range of topics which were received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe loss of biodiversity, impacts on culturally important native plants and animals, increases in invasive species, bark beetle damage to forests and increased risk of forest fires that have been observed in the Southwest U.S. and across much of the West (ITEP 2011). Climate drivers associated with this key message are also discussed in the climate science chapter. There are also many relevant and recent peer-reviewed publications (Trainor et al. 2009) describing the northward migration of the boreal forest and changes in the distribution and density of wildlife species that have been observed. Observed impacts on plant and animal species including species loss and shifts in species range is well documented (Louisiana Workshop 2012; Swinomish Indian

	Tribal Community 2010).
New information and remaining uncertainties	A key uncertainty is how indigenous people will adapt to climate change, given their reliance on local, wild foods and the isolated nature of some communities, coupled with their varied preparedness and limited ability to deal with wildfires. Increased wildfire occurrences may affect tribal homes, safety, economy, culturally important species, medicinal plants, traditional foods, and cultural sites. There is uncertainty as to the extent that Native American and Alaska Natives' access to traditional foods such as salmon, shellfish, crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations will be affected by climate change.
Assessment of confidence based on evidence	Based on the evidence, confidence is **very high** that climate change related impacts, such as increased frequency and intensity of wildfires, higher temperatures, ecosystem changes, ocean acidification, forest loss and habitat damage, are threatening Native American and Alaska Natives' access to traditional foods such as salmon, shellfish, crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 12: Tribal, Indigenous, and Native Lands and Resources

Key Message Process: See key message #1.

Key message #2/5	**A decrease in water quality and quantity, caused by a variety of factors including climate change, is affecting Native Americans and Alaska Natives' drinking water supplies, food, cultures, ceremonies, and traditional ways of life. Native communities' vulnerabilities and lack of capacity to adapt to climate change are exacerbated by land-use policies, political marginalization, legal issues associated with tribal water rights, and poor socioeconomic conditions.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics which were received and reviewed as part of the Federal Register Notice solicitation for public input. There are numerous examples of Tribal observations of changes in precipitation, and impacts on surface water features, agriculture, grazing, medicinal and culturally important plants and animals, water resources, rainfall patterns and storm intensity. (Christensen 2003; Ferguson and Crimmins 2009; Garfin et al. 2012; Hiza et al. 2011). Examples of ceremonies are included in the Oklahoma Inter-Tribal Meeting on Climate Variability and Change, Meeting Summary Report (Riley et al. 2012). Water is used for some ceremonies, so it can be problematic when there is not enough at the tribe's disposal (Riley et al. 2012). More than one tribe at the meeting also expressed how heat has been a problem during ceremonies, since the older citizens cannot go into non-air conditioned lodges (Riley et al. 2012).
New information and remaining uncertainties	There is limited data to establish baseline climatic conditions on tribal lands, and many tribes do not have sufficient capacity to monitor changing conditions (Ferguson et al. 2011). Without monitoring, tribal decision-makers lack the data needed to quantify and evaluate the current conditions and emerging trends in precipitation, streamflow, and soil moisture, and to plan and manage resources accordingly (Collins et al. 2010; Garfin et al. 2012). Water infrastructure is in disrepair or lacking on some reservations (Ojima et al. 2012; Redsteer et al. 2011b). There is an overall lack of financial resources to support basic water infrastructure on tribal lands (Ferguson et al. 2011). Uncertainty associated with undefined tribal water rights make it difficult to determine strategies to deal with water resource issues (Ojima et al. 2012). Tribes that rely on water resources to maintain their cultures, religions, and lifeways are especially vulnerable to climate change. Monitoring data is needed to establish baseline climatic conditions and to monitor changing conditions on tribal lands. Uncertainty associated with undefined tribal water rights make it difficult to determine strategies to deal with water resource issues.
Assessment of confidence based on evidence	Based on the evidence, confidence is **very high** that decreases in water quality and quantity are affecting Native Americans and Alaska Natives' drinking water supplies, food, cultures, ceremonies, and traditional ways of life.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 12: Tribal, Indigenous, and Native Lands and Resources

Key Message Process: See key message #1.

Key message #3/5	**Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and/or loss of homes and settlements, food insecurity from changing availability of wild food sources, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics which were received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence that summer sea ice is rapidly declining is based on satellite data, and other observational data and is incontrovertible. Although there is disagreement among models about the rate of sea ice loss projected ice free summers by 2100, more recent CMIP5 models that most accurately reconstruct historical sea ice loss do project that late-summer sea ice will disappear by the 2030s (see Climate Science and Alaska Chapters). Evidence that sea ice loss is altering marine ecosystems; allowing for greater ship access and new development; increasing Native community vulnerabilities due to changes in sea ice thickness and extent; destroying housing, village sanitation and other infrastructure (including entire villages); increasing food insecurity from lack of access to subsistence food and loss of cultural traditions are all well-documented in field studies, Indigenous knowledge, and scientific literature (C. Pungowiyi 2006, personal communication, 2009, personal communication; Gearheard et al. 2010; Laidler et al. 2009).
New information and remaining uncertainties	A key uncertainty is how Indigenous peoples will be able to maintain historical subsistence ways of life which include hunting, fishing, harvesting, and sharing and sustain the traditional relationship with the environment given the impacts from sea ice decline and changes. Increased sea ice changes and declines are already causing increasingly hazardous hunting and traveling conditions along ice edges, damage to homes and infrastructure from erosion, changes in habitat for subsistence foods and species and with overall impacts on food insecurity, and species necessary for medicines, ceremonies, and other traditions. The effects of sea ice loss are exacerbated by other climate change driven changes such as changes in snow and ice, weather, and in-migration of people, poverty, lack of resources to respond to changes, and contamination of subsistence foods. Additional observations and monitoring are needed to more adequately document ice and weather changes.
Assessment of confidence based on evidence	Based on the evidence, there is **very high** confidence that loss of sea ice is affecting the traditional life ways of Native communities in a number of important ways such as increased hazardous travel and hunting conditions along the ice edge, erosion damage to homes, infrastructure, sanitation facilities (including loss of entire villages), changes in ecosystem habitats and, therefore, impacts on food security, and socioeconomic and health impacts from cultural and homeland losses.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 12: Tribal, Indigenous, and Native Lands and Resources

Key Message Process: See key message #1.

Key message #4/5	**Alaska Native communities are increasingly exposed to health and livelihood hazards from permafrost thawing and increasing temperatures, which are causing damage to roads, water supply and sanitation systems, homes, schools, ice cellars, and ice roads, and threatening traditional lifestyles.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics which were received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe evidence that incontrovertible permafrost thaw is taking place, and models project an increased rate for at least the next 100 years. There are also many relevant and recent peer-reviewed publications (McClintock 2009; University of Oregon 2011b) describing the impact of permafrost thaw on Alaska Native villages. Over 30 Native villages in Alaska are in need of or in the process of being moved. Recent work (Bender et al. 2011; Parkinson and Evengård 2009) documents public health issues such as contamination of clean water for drinking and hygiene and food insecurity through thawing of ice cellars for subsistence food storage.
New information and remaining uncertainties	Improved models and observational data (see Alaska Chapter) confirmed many of the findings from prior Alaska assessment; see (http://www.globalchange.gov/publications/reports/scientificassessments/us-impacts/regional-climate-change-impacts/alaska). A key uncertainty is how Indigenous peoples in Alaska will be able to sustain traditional subsistence life ways when their communities and settlements on the historical lands of their ancestors are collapsing due to permafrost thawing, flooding, and erosion combined with loss of shore fast ice, sea level rise, and severe storms, especially, along the coasts and rivers. Another uncertainty is how indigenous communities can protect the health and welfare of the villagers from permafrost thaw-caused public health issues of drinking water contamination and loss of traditional food storage and potential contamination. It is uncertain how Native communities will be able to effectively relocate and maintain their culture, particularly because there are no institutional frameworks, legal authorities or funding to implement relocation for communities forced to relocate.
Assessment of confidence based on evidence	Based on the evidence, confidence is **very high** that Alaska Native communities are increasingly exposed to health and livelihood hazards from permafrost thawing and increasing temperatures, which are causing damage to roads, water supply and sanitation systems, homes, schools, ice cellars, and ice roads, and threatening traditional lifestyles.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 12: Tribal, Indigenous, and Native Lands and Resources

Key Message Process: See key message #1.

Key message #5/5	**Accelerated sea level rise, erosion, permafrost thaw, and/or increased intensity of weather events are forcing relocation of entire tribal and indigenous communities in Alaska, Louisiana, the Pacific Islands, and other coastal locations. These relocations and the lack of governance mechanisms or funding to support them are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics which were received and reviewed as part of the Federal Register Notice solicitation for public input. There is well-documented evidence that Tribal communities are vulnerable to coastal erosion that could force them to relocate. (Galloway McLean 2009; GAO 2009). For example, tribal communities in Alaska, such as Newtok, Kivalina and Shishmaref, are experiencing accelerated rates of erosion caused by the combination of decreased Arctic sea ice, thawing permafrost, and increased intensity of weather events, resulting in loss of basic necessities and infrastructure (Bronen 2011; Shearer 2012). Tribal communities in Coastal Louisiana are experiencing climate-induced rising sea levels, along with saltwater intrusion and intense erosion and land loss due to oil and dam development, forcing them to either relocate or try to find ways to save their land (Louisiana Workshop 2012). Native Pacific Island communities are being forced to consider relocation plans due to increasing sea level rise and storm surges.
New information and remaining uncertainties	A key uncertainty is the extent that the combination of other impacts (e.g., erosion caused by dredging for oil pipelines or second-order effects from adaptation-related development projects) will coincide with sea level rise and other climate-related issues to increase the rate at which communities will need to relocate. Another key uncertainty is how communities will be able to effectively relocate, maintain their communities and culture and reduce the impoverishment risks that often go along with relocation. The United States lacks an institutional framework to relocate entire communities, and national, state, local, and tribal government agencies lack the legal authority and the technical, organizational, and financial capacity to implement relocation processes for communities forcibly displaced by climate change.
Assessment of confidence based on evidence	Based on the evidence, there is **very high** confidence that Tribal communities in Alaska, Coastal Louisiana, Pacific Islands, and other coastal locations are being forced to relocate due to sea level rise, coastal erosion, melting permafrost, and/or increased intensity of weather events.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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13. Land Use and Land Cover Change

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Key Messages

1. **Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.**
2. **Land-use and land-cover changes affect local, regional, and global climate processes.**
3. **Individuals, organizations, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.**
4. **Choices about land use and land management provide a means of reducing atmospheric greenhouse gas levels.**

In addition to emissions of greenhouse gases from energy, industrial, agricultural, and other activities, humans affect climate through changes in how we use land (such as growing food, cutting trees, or building cities) and what we put on the land (such as planting grain crops and new trees or pouring concrete) (Loveland et al. 2012). For example, cities are warmer than the surrounding countryside because of the greater extent of paved areas in the cities, which affects how water and energy are exchanged between the land and the atmosphere, and how exposed the population is to extreme heat events. Decisions about land use and land cover can therefore affect, positively or negatively, how much our climate will change, and what kind of vulnerabilities that humans and natural systems will face as a result.

The impacts of changes in land use and land cover cut across all regions and sectors of the National Climate Assessment. Chapters addressing each region discuss land use and land cover topics of particular concern to specific regions. Similarly, chapters addressing sectors examine specific land use matters. In particular, land cover and land use are a major focus for sectors such as agriculture, forestry, rural and urban communities, or Native American lands. By contrast, the key messages of this chapter are national in scope and synthesize the findings of other chapters regarding land cover and land use.

Land uses and land covers change over time in response to evolving economic, social, and biophysical conditions (Lebow et al. 2012). Many of these changes are set in motion by individual landowners and land managers and can be quantified from satellite measurements, aerial photographs, and on-the-ground observations (Loveland et al. 2002). Over the past few decades, the most prominent land changes within the U.S. have been the amount and kind of forest cover due to logging practices and development in the Southeast and Northwest, and to urban expansion in the Northeast and Southwest.

Because humans control land use and, to a large extent, land cover, individuals, organizations, and governments can make land decisions to adapt to and/or reduce the effects of climate change. Adaptation options include varying the local mix of vegetation and concrete to reduce heat in cities, or elevating homes to reduce exposure to sea level rise or flooding. Land use and land-cover related options for reducing the speed and amount of climate change include expanding forests to accelerate removal of carbon from the atmosphere, modifying the way cities are built and organized to reduce energy and motorized transportation demands, and altering agricultural management practices to increase carbon storage in soil. The term “mitigation” is often used for these kinds of activities that can reduce future climate change.

Despite this range of climate change response options, there are two main reasons why private and public landowners may not choose to modify land uses and land covers for climate adaptation or mitigation purposes. First, land decisions are influenced not only by climate but also by economic, cultural, legal, or other considerations. In many cases, climate-based land-change efforts to adapt to or reduce climate change meet with resistance because current practices are deeply entrenched in local economies and cultures. Second, certain land uses and land covers are simply difficult to modify, regardless of desire or intent. For instance, the number of homes constructed in floodplains or the amount of irrigated agriculture can be so deeply rooted that they are difficult to change, no matter how much those practices might impede our ability to respond to climate change.

Recent Trends

In terms of land area, the U.S. remains a predominantly rural country, even as its population increasingly gravitates towards urban areas. In 1910, only 46% of the U.S. population lived in urban areas, but by 2010 that figure had climbed to more than 81% (U.S. Census Bureau 1995, 2012). Even with those large population shifts, in 2006 (the most recent year for which these data are available) more than 80% of the land cover in the lower 48 states was still dominated by shrub/scrub vegetation, grasslands, forests, and agriculture (Fry et al. 2011; Homer et al. 2007). Forests and grasslands, which include acreage used for timber production and grazing, account for more than half of all U.S. land use by area (Table 1) (Nickerson et al. 2011). Agricultural uses account for about 20% of our surface area. Developed or built-up areas covered only about five percent of the country’s land surface, with the greatest concentrations of urban areas in the Northeast, Midwest, and Southeast. This apparently small percentage of developed area belies its rapid expansion and does not include development that is dispersed in a mosaic among other land uses (like agriculture and forests). In particular, low-density housing developments (suburban and exurban areas) have rapidly expanded throughout the U.S. over the last 60 years or so (Brown et al. 2005; Hammer et al. 2009; Solecki and Rosenzweig 2012). Areas settled at suburban and exurban densities (1 house per 1 to 40 acres on average) now cover more than 15 times the land area of areas settled at urban densities (1 house per acre or less).

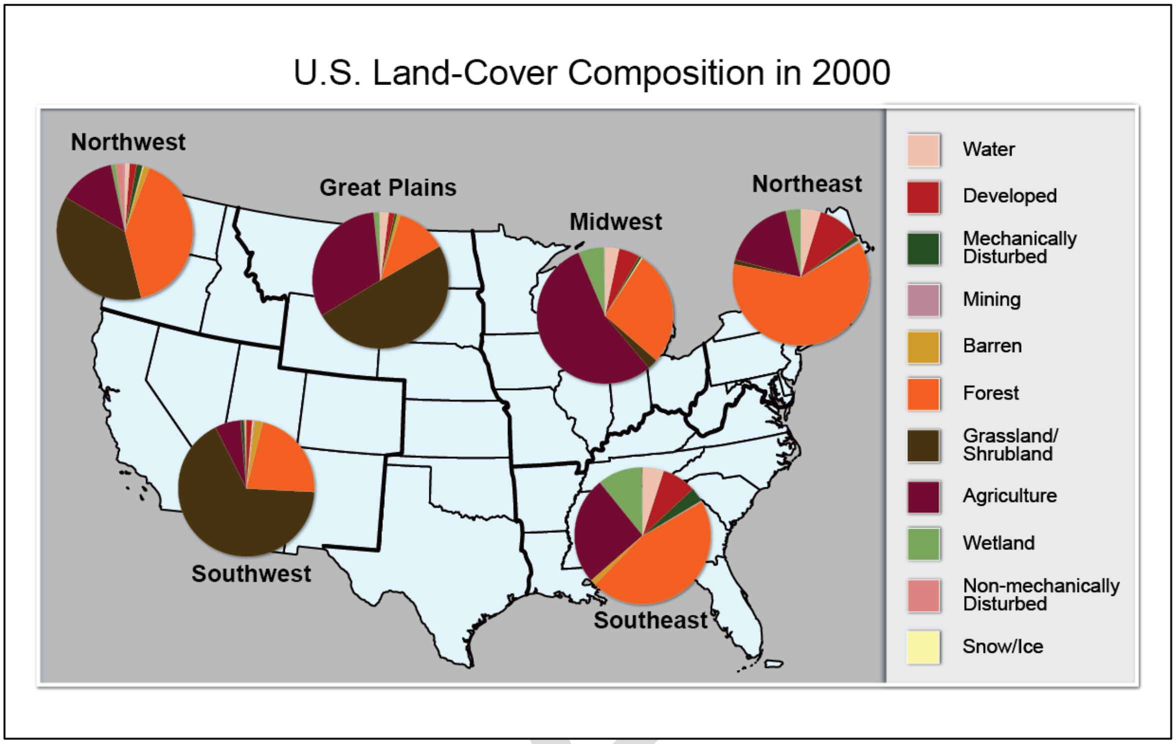

Figure 13.1. U.S. Land-Cover Composition in 2000

Caption: Map shows regional differences in land cover. These patterns affect climate and will be affected by climate change. They also influence the vulnerability and resilience of communities to the effects of climate change (Figure source: USGS Earth Resources Observation and Science (EROS) Center. Data from USGS Land Cover Trends Project).

Despite these rapid changes in developed land covers, the vast size of the country means that total land-cover changes in the U.S. may appear deceptively modest. Since 1973, satellite data show that the overall rate of land-cover changes nationally has averaged about 0.33% per year. Yet this small rate of change has produced a large cumulative impact. Between 1973 and 2000, 8.6% of the area of the lower 48 states experienced land-cover change, an area roughly equivalent to the combined land area of California and Oregon (Loveland et al. 2012).

These national-level annual rates of land changes mask considerable geographic variability in the types, rates, and causes of change (Loveland et al. 2002). Between 1973 and 2000, the Southeast region had the highest rate of change, due to active forest timber harvesting and replanting, while the Southwest region had the lowest rate of change. Satellite observations also tend to underestimate urban development, especially where settlement occurs at low densities. Other analyses show that suburban and exurban areas increased fivefold in size between 1950 and 2000 (Brown et al. 2005).

Table 13.1. Circa-2001 land-cover statistics for the National Climate Assessment regions of the United States (Homer et al. 2007), and overall United States land-use statistics—circa 2007 (Nickerson et al. 2011).

Land Cover Class	Northeast	Southeast	Midwest	Great Plains	Southwest	Northwest	Alaska	Hawaii	United States	Land Use Class (ca 2007)	United States (ca 2007)
Agriculture	10.9%	23.0%	49.0%	29.7%	5.0%	10.0%	0.0%	4.0%	18.60%	Cropland	18.0%
Grassland, Shrub/Scrub, Moss, Lichen	3.4%	7.8%	2.9%	50.5%	65.7%	42.8%	44.9%	33.3%	39.2%	Grassland, Pasture, and Range	27.1%
Forest	52.4%	38.7%	23.7%	10.7%	19.9%	37.7%	22.4%	22.0%	23.2%[1]	Forest	29.7%[1]
Barren	0.8%	0.3%	0.2%	0.5%	3.7%	1.5%	7.7%	11.2%	2.6%	Special Use[2]	13.8%
Developed, Built-Up	9.6%	7.7%	8.0%	4.0%	2.7%	3.0%	0.1%	6.7%	4.0%	Urban	2.7%
Water, Ice, Snow	14.9%	7.3%	10.4%	1.9%	1.7%	3.2%	18.5%	21.7%	7.4%	Misc-ellaneous[3]	8.7%
Wetlands	8.0%	15.2%	5.8%	2.7%	0.7%	1.3%	6.4%	0.3%	5.0%		

[1] Definitional differences, such as the special uses distinction in the USDA Economic Research Service land use estimates, make direct comparisons between land use and land cover challenging. For example, forest land use (29.7%) exceeds forest cover (23.2%). Forest use definitions include lands where trees have been harvested and may be replanted, while forest cover is a measurement of the presence of trees.

[2] Special uses represent rural transportation, rural parks and wildlife, defense and industrial, plus miscellaneous farm and other special uses.

[3] Miscellaneous uses represent unclassified uses such as marshes, swamps, bare rock, deserts, tundra plus other uses not estimated, classified, or inventoried.

Table 13.2. Percentage net and gross land-cover change (1973-2000) for the conterminous United States National Climate Assessment regions. Net change is the percent change in the area of each land-cover type. Gross change is the percentage of the total area of the land-cover type at the first time that was modified between two periods (for example, includes increases in forest cover and decreases in forest cover).

	Northeast		Southeast		Midwest		Great Plains		Southwest		Northwest	
Land Cover Type	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross
Grassland/Shrubland	0.73	1.14	0.31	0.91	0.59	1.35	1.55	5.29	-0.28	2.51	0.35	4.58
Forest	-2.02	4.05	-2.51	7.91	-0.93	2.26	-0.71	1.50	-0.49	0.75	2.39	6.04
Agriculture	-0.85	1.48	-1.62	3.67	-1.38	2.74	-1.60	4.82	-0.37	1.73	-0.35	1.94
Developed	1.36	1.37	2.28	2.30	1.34	1.35	0.43	0.43	0.51	0.52	0.51	0.51
Mining	0.14	0.53	-0.05	0.47	0.02	0.13	0.07	0.09	0.10	0.12	0.03	0.05
Barren	0.00	0.01	-0.01	0.03	0.00	0.01	0.00	0.09	0.00	0.02	0.00	0.05
Snow/Ice	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.03	0.06	0.45	0.64	0.08	0.25	0.23	0.46	0.03	0.13	-0.02	0.12
Wetland	-0.05	0.08	-0.69	1.31	-0.05	0.34	-0.13	0.40	-0.02	0.12	0.03	0.12
Mechanically Disturbed [1]	0.66	1.42	1.76	3.90	0.32	0.81	0.11	0.52	0.07	0.22	0.07	2.71
Non-mechanically Disturbed [2]	0.00	0.00	0.07	0.10	0.01	0.01	0.06	0.18	0.46	0.55	1.78	2.10

[1] Land in an altered and often un-vegetated state that, because of disturbances by mechanical means, is in transition from one cover type to another. Mechanical disturbances include forest clear-cutting, earthmoving, scraping, chaining, reservoir drawdown, and other similar human-induced changes.

[2] Land in an altered and often un-vegetated state that because of disturbances by non-mechanical means, is in transition from one cover type to another. Non-mechanical disturbances are caused by fire, wind, floods, animals, and other similar phenomena.

Projections

Future patterns of land use and land cover will interact with climate changes to affect human communities and ecosystems. At the same time, future climate changes will also affect how and where humans live and use land for various purposes.

National-scale analyses suggest that the general historical trends of land use and land-cover changes (described above) will continue, with some important regional differences. These projections all assume continued population growth, which will result in changes in land use and land cover that are spread unevenly across the U.S. Urban areas are projected to increase at the slowest rate in the Northeast region, because of the high level of existing development and relatively low rates of population growth, and at highest rate in the Northwest. In terms of area, the Northwest has the smallest projected increase in urban area (approximately 4.2 million acres), and the Southeast the largest (approximately 27.5 million acres) (Wear 2011).

Some of the projected changes in developed areas will depend on assumptions about changes in household size, and how concentrated urban development will be. Higher population density means less land is converted from forests or grasslands, but results in a greater extent of paved area. Projected growth in low-density exurban areas will result in a greater area affected by development, and is expected to increase commuting times and infrastructure costs. The areas projected to experience exurban development will have less density of impervious surfaces (like asphalt or concrete). While exurban areas have about one-third of their area covered by impervious surfaces (Bierwagen et al. 2010), urban or suburban areas are about one-half concrete and asphalt.

Projected land-use and land-cover changes will depend to some degree on rates of population and economic growth. In general, scenarios of continued high growth produce more rapid increases in developed areas of all densities and in areas covered by impervious surfaces (paved areas and buildings) by 2050 (Bierwagen et al. 2010; Wear 2011). Exurban and suburban areas are projected to expand by 15% to 20% between 2000 and 2050 (Bierwagen et al. 2010). Cropland and forest are projected to decline most under a scenario of high population and economic growth and least under lower-growth scenarios. More forest than cropland is projected to be lost in the Northeast and Southeast, whereas more cropland than forest is projected to be lost in the Midwest and Great Plains (Sohl et al. 2012). Some of these differences are due to the current mix of land uses, others to the differential rates of urbanization in these different land uses.

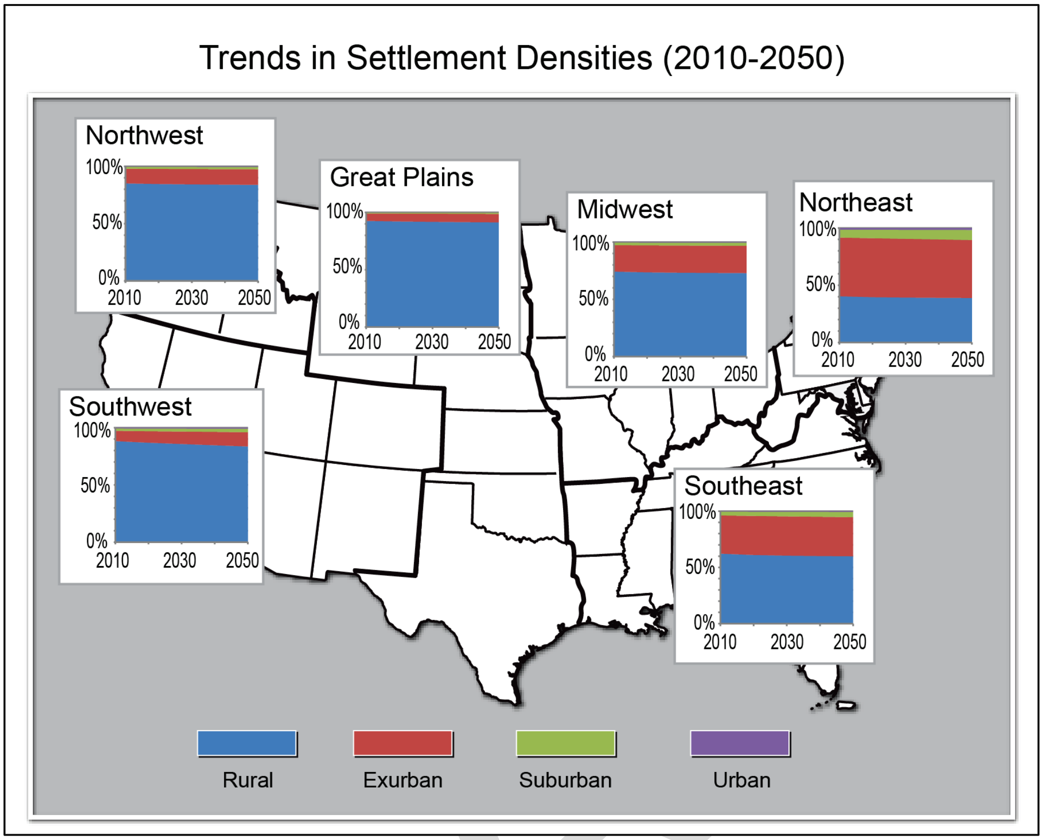

Figure 13.2: Trends in Settlement Densities (2010-2050)

Caption: Projected percentages in each housing-unit density category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2 scenario). Data source: U.S. EPA Integrated Climate and Land Use Scenarios.

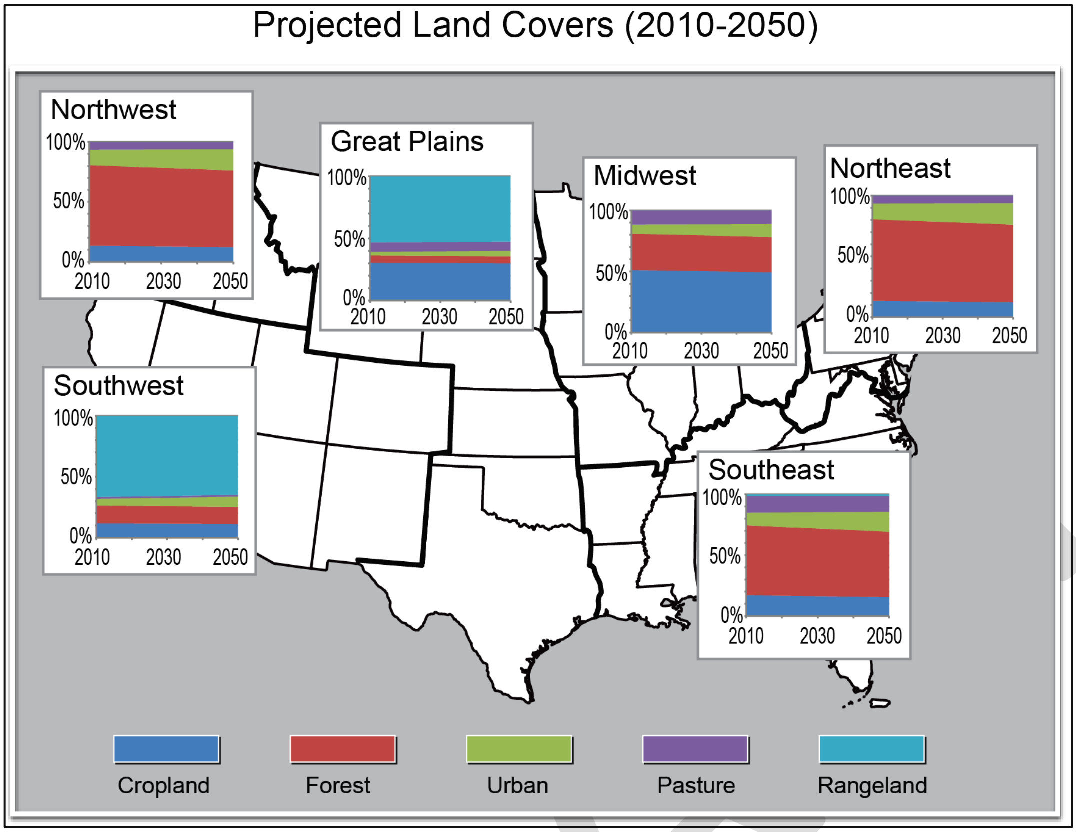

Figure 13.3. Projected Land Covers (2010-2050)

Caption: Projected percentages in each land-cover category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2 scenario) (Data source: Wear et al., 2011)

Effects on Communities and Ecosystems

Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.

Decisions about land-use and land-cover change by individual landowners and land managers are influenced by demographic and economic trends and social preferences, which unfold at global, national, regional and local scales. Policymakers can directly affect land use through mandates and regulations, and/or by creating financial incentives. For example, Congress can declare an area as federally protected wilderness, or local officials can set aside portions of a town for industrial development and create tax benefits for companies to build there. However, climate factors typically play a secondary role in land decisions, if they are considered at all. Nonetheless, land change decisions may affect the vulnerabilities of households, organizations, and communities to the effects of climate change. A farmer's choice of crop rotation in response to price signals affects his or her farm income's susceptibility to drought, for example. Similarly, a developer's decision to build new homes in a floodplain may affect the new homeowners' vulnerabilities to flooding events.

The combination of residential location choices with wildfire occurrence dramatically illustrates how the interactions between land use and climate processes can affect climate change impacts and vulnerabilities. Low-density housing patterns in the U.S. have expanded, and are projected to continue to expand (Bierwagen et al. 2010). One result is a rise in the amount of construction in forests and other wild-lands (Radeloff et al. 2005; Theobald and Romme 2007) that in turn has increased the exposure of houses, other structures, and people to damages from wildfires, which are increasing. The number of buildings lost in the 25 most destructive fires in California history increased significantly in the 1990s and 2000s compared to the previous three decades (Stephens et al. 2009). These losses are one example of how changing development patterns can interact with a changing climate to create dramatic new risks. In the western U.S., increasing frequencies of large wildfires and longer wildfire durations are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt (Westerling et al. 2006). The effects on property loss of increases in the frequency and sizes of fires under climate change are also projected to increase in the coming decades because so many more people will have moved into increasingly fire-prone places (Ch. 2: Our Changing Climate; Ch. 7: Forestry).

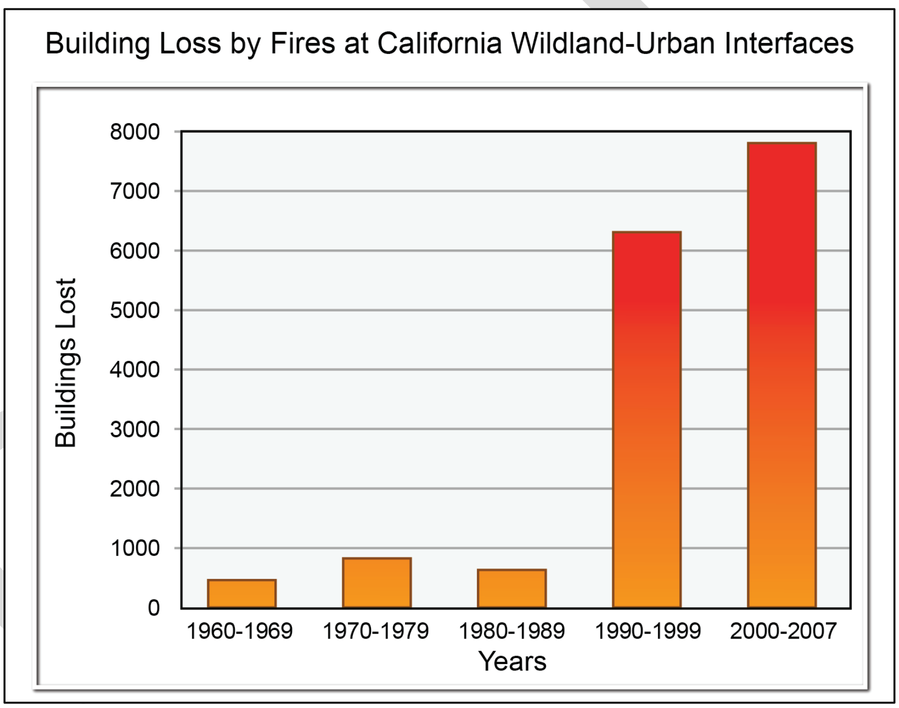

Figure 13.4. Building Loss by Fires at California Wildland-Urban Interfaces

Caption: Many forested areas in the U.S. have experienced a recent building boom in what is known as the "wildland-urban interface." Chart shows number of buildings lost from the 25 most destructive wildland-urban interface fires in California history from 1960–2007 (Redrawn from Stephens et al. 2009 with permission).

Effects on Climate Processes

Land-use and land-cover changes affect local, regional, and global climate processes.

Land use and land cover play critical roles in the interaction between the land and the atmosphere, influencing climate at local, regional, and global scales (Pielke 2005). There is growing evidence that land use and land cover interact with U.S. climate in several ways:

- Air temperature and near-surface moisture are changed in areas where natural vegetation is converted to agriculture (Fall et al. 2010; Karl et al. 2012). This effect has been observed in the Great Plains and the Midwest, where overall dew point temperatures or frequency of occurrences of extreme dew point temperatures have been increased due to converting land to agricultural use (Karl et al. 2012; Mahmood et al. 2008; McPherson et al. 2004; Sandstrom et al. 2004). This effect has also been observed where the fringes of California's Central Valley is being converted from natural vegetation to agriculture (Sleeter 2008). Other areas where uncultivated and conservation lands are being returned to cultivation, for example from restored grassland into biofuel production, have also experienced temperature shifts. Regional daily maximum temperatures were lowered by forest clearing for agriculture in the Northeast and Midwest, and then increased in the Northeast following regrowth of forests due to abandonment of agriculture (Bonan 2001).

- Conversion of rain-fed cropland to irrigated agriculture further intensifies the impacts of agricultural conversion on temperature. Lobell and Bonfils (2007) found up to 5°C (9°F) cooling of daily maximum temperatures in California due to irrigation. Model comparisons suggest that irrigation cools temperatures directly over croplands in California's Central Valley by 5°F to 13°F, and increases relative humidity by 9% to 20% (Sorooshian et al. 2011). Observational data-based studies found similar impacts of irrigated agriculture in the Great Plains (Lobell et al. 2006; Mahmood et al. 2008).

- Both observational and modeling studies show that introduction of irrigated agriculture can impact regional precipitation (Barnston and Schickedanz 1984; DeAngelis et al. 2010; Harding and Snyder 2012a, 2012b). It has been shown that irrigation in the Ogallala aquifer portion of the Great Plains can impact precipitation as far away as Indiana and Western Kentucky (DeAngelis et al. 2010).

- Urbanization is having significant local impacts on weather and climate. Land-cover changes associated with urbanization are creating higher air temperatures compared to the surrounding rural area (Arnfield 2003; Landsberg 1970; Shepherd et al. 2002; Souch and Grimmond 2006; Yow 2007). This is known as the "urban heat island" effect (see Ch. 9: Health). Urban landscapes are also affecting formation of convective storms and changing the location and amounts of precipitation compared to pre-urbanization, (for example, Niyogi et al. 2011; Shepherd et al. 2002).

- Land-use and land-cover changes are affecting global atmospheric concentrations of greenhouse gases. The impact is expected to be most significant in areas with forest loss or gain, where the amount of carbon that can be transferred from the atmosphere to the land (or from the land to the atmosphere) is modified. Even in relatively un-forested areas, this effect can be significant. A recent USGS report suggests that from 2001–2005 in the Great Plains between 22–106 million metric tons of carbon were stored in the biosphere due to changes in land use and climate (Zhu et al. 2011). Even with these seemingly large numbers, U.S. forests absorb only 7% to 24% (with a best estimate of 13%) of fossil-fuel CO_2 emissions (see Ch. 15: Biogeochemical Cycles, "Carbon Sink" box).

Adapting to Climate Change

Individuals, organizations, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.

Land-use and land-cover patterns may be modified to adapt to anticipated or observed effects of a changed climate. These changes may be either encouraged or mandated by government (whether at federal or other levels), or undertaken by private initiative. In the U.S., even though land-use decisions are highly decentralized and strongly influenced by Constitutional protection of private property, the Supreme Court has also defined a role for government input into some land-use decisions (Berke and Kaiser 2006). Thus on the one hand farmers may make private decisions to plant different crops in response to changing growing conditions and/or market prices. On the other hand, homeowners may be compelled to respond to policies, zoning, or regulations (at national, state, county, or municipal levels) by elevating their houses to reduce flood impacts associated with more intense rainfall events and/or increased impervious surfaces.

Land-use and land-cover changes are thus rarely the product of a single factor. Land-use decision processes are influenced not only by the biophysical environment, but also by markets, laws, technology, politics, and perceptions. Yet there is evidence that climate adaptation considerations are playing an increasingly large role in land decisions, even in the absence of a formal federal climate policy. Motivations typically include avoiding or reducing negative impacts from extreme weather events (such as storms or heat waves) or from slow-onset hazards (such as sea level rise).

For example, New Orleans has, through a collection of private and public initiatives, rebuilt some of the neighborhoods damaged by Hurricane Katrina with housing elevated several meters above the ground, and with roofs specially designed to facilitate evacuation (ISC 2010). San Francisco has produced a land-use plan to reduce impacts from a rising San Francisco Bay (SFBCDC 2011). A similar concern has prompted collective action in four Miami-area counties and an array of San Diego jurisdictions, to name just two examples, to shape future land uses to comply with regulations linked to sea level rise projections (ICLEI 2011; ISC 2010). Chicago has produced a plan for limiting the number of casualties, especially among the elderly and homeless, during heat waves (ISC 2010; See also Ch. 9: Health).

Reducing Greenhouse Gas Levels

Choices about land use and land management provide a means of reducing atmospheric greenhouse gas levels.

Choices about land use and land management affect the amount of greenhouse gases entering and leaving the atmosphere and, therefore, provide opportunities to reduce climate change (Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation). Such choices can affect the balance of these gases directly, through decisions to preserve or restore carbon in standing vegetation (like forests) and soils, and indirectly, in the form of land use policies that affect fossil fuel emissions by influencing energy consumption for transportation and in buildings. Additionally, as crops are increasingly used to make fuel, the potential for reducing net carbon emissions through replacement of fossil fuels represents a possible land-based carbon emissions reduction strategy, albeit one that is complicated by many natural and economic interactions that will determine the ultimate effect of these strategies on emissions (Ch. 7: Forestry; Ch. 6: Agriculture).

About one-third of all carbon released into the atmosphere by people globally since 1850 has come from land-cover change and management. The primary source related to land use has been the conversion of native vegetation like forests and grasslands to croplands, which in turn has released carbon from vegetation and soil into the atmosphere as carbon dioxide (CO_2) (Richter and Houghton 2011). Currently, an estimated 16% of CO_2 going into the atmosphere is due to land-related activities globally, with the remainder coming from fossil fuel burning and cement manufacturing (Richter and Houghton 2011). In the U.S., activities related to land use are effectively balanced with respect to CO_2: as much CO_2 is released to the atmosphere by land-use activities as is taken up by and stored in, for example, vegetation and soil. The regrowth of forests and increases of conservation-related forest and crop management practices have also increased carbon storage. Overall, setting aside emissions due to burning fossil fuels, the U.S. and the rest of North American land cover takes up more carbon than it releases. This has happened as a result of more efficient forest and agricultural management practices, but it is not clear if this rate of uptake can be increased, or if it will persist into the future. The magnitude of the sink can vary with weather, making it potentially sensitive to climate changes (Schwalm et al. 2012).

Opportunities to increase the net uptake of carbon from the atmosphere by the land include: increasing the amount of area in ecosystems with high carbon content (by converting farms to forests or grasslands); increasing the rate of carbon uptake in existing ecosystems (through fertilization); and reducing carbon loss from existing ecosystems (for example, through no-till farming) (Izzauralde 2012). Because of these effects, policies specifically aimed at increasing carbon storage, either directly through mandates or indirectly through a market for carbon offsets, may be used to encourage more land-based carbon storage.

The following uncertainties deserve further investigation: a) the effects of these policies or actions on the balance of other greenhouse gases, like methane and nitrous oxide; b) the degree of permanence these carbon stores will have in a changing climate (especially through effects on disturbances like fires and plant pests); and c) the possibility that increased carbon storage in one location might be partially offset by releases in another. All of these specific mitigation options present implementation challenges, as the decisions must be weighed against competing objectives. For example, retiring farmland to sequester carbon may be difficult to achieve if crop prices rise, such as has occurred in recent years in response to the fast-growing market for biofuels.

Land-use decisions in urban areas also present carbon reduction options. Carbon storage in urban areas can reach densities as high as those found in tropical forests, with most of that carbon found in soils, but also in vegetation, landfills, and the structures and contents of buildings (Churkina et al. 2010). Urban and suburban areas tend to be net sources of carbon to the atmosphere, whereas exurban and rural areas tend to be net sinks (Zhao et al. 2011). Effects of urban development patterns on carbon storage and emissions due to land and fossil fuel use are topics of current research, and can be affected by land-use planning choices. Many cities have adopted land-use plans with explicit carbon goals, typically targeted at reducing carbon emissions from the often intertwined activities of transportation and energy use. This trend, which includes both major cities, such as Los Angeles (EnvironmentLA 2011), Chicago (City of Chicago 2012), and New York City (NYCDEP 2011), and small towns, such as Homer, Alaska (City of Homer 2007), has occurred even in the absence of a formal federal climate policy.

Traceable Accounts

Chapter 13. Land Use and Land Cover Change

Key Message Process: The author team benefited from a number of relevant technical input reports. One report described the findings of a three-day workshop held from November 29 to December 1, 2011 in Salt Lake City in which a number of the chapter authors participated (Lebow et al. 2012). Findings of the workshop provided a review of current issues and topics as well as the availability and quality of relevant data. In addition, From December, 2011 through June, 2012 the author team held biweekly teleconferences. Key messages were identified during this period and discussed in two phases, associated with major chapter drafts. An early draft identified a number of issues and key messages. Based on discussions with assessment leadership and other chapter authors, the Land Use and Land Cover Change authors identified and reached consensus on a final set of four key messages and organized most of the chapter to directly address these messages. The authors selected key messages based on the consequences and likelihood of impacts, the implied vulnerability, and available evidence. Relevance to decision support, mitigation, and adaptation was also an important criterion for the selection of key messages for this cross-cutting and foundational topic.

The U.S. acquires, produces, and distributes substantial data that characterize the Nation's land cover and land use. Satellite observations, with near complete coverage over the landscape and consistency for estimating change and trends, are particularly valuable. But field inventories, especially of agriculture and forestry, provide very reliable data products that describe land cover as well as land-use change. Together, remote sensing and field inventory data as well as related ecological and socioeconomic data allow many conclusions about land use and land-cover change with very high confidence.

Key message #1/4	**Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.**
Description of evidence base	The influences of climate on vegetation and soils, and thus on land cover and land use, are relatively well understood, and a number of well validated mathematical models are used to investigate potential consequences of climate change for ecosystem processes, structure, and function. Given scenarios about socioeconomic factors or relevant models, some aspects of land use and land-cover change can also be analyzed and projected into the future based on assumed climate change. A large number of studies documented in the literature address the impacts of weather events and climate variability and change on land cover and land use. During a workshop convened to review land use and land-cover change for the NCA, participants summarized various studies from different perspectives, including agriculture and forestry as well as socioeconomic issues such as flood insurance (Lebow et al. 2012). Residential exposure to wildfire is an excellent example supporting this key message, and is well documented in the literature (Radeloff et al. 2005; Stephens et al. 2009; Theobald and Romme 2007; Westerling et al. 2006).
New information and remaining uncertainties	Steadily accumulating field and remote sensing observations as well as inventories continue to increase confidence in this key message. A recent study by the EPA (Bierwagen et al. 2010) provides relevant projections of housing density and impervious surface under alternative scenarios of climate change. While there is little uncertainty about the general applicability of this key message, the actual character and consequences of climate change as well as their interactions with land cover and land use vary significantly between locations and circumstances. Thus the specific vulnerabilities resulting from the specific ways in which people, both as individuals and as collectives, will respond to anticipated or observed climate change impacts are less well understood than the biophysical

	dimensions of this problem.
Assessment of confidence based on evidence	**Very High.** Observed weather and climate impacts and consequences for land cover and land use, basic understanding of processes and analyses using models of those processes, as well as substantial literature are consistent in supporting this key message.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 13. Land Use and Land Cover Change

Key Message Process: See key message #1.

Key message#2/4	**Land-use and land-cover changes affect local, regional, and global climate processes.**
Description of evidence base	The dependence of weather and climate processes on land surface properties is reasonably well understood in terms of the biophysical processes involved. Most climate models represent land-surface conditions and processes, though only recently have they begun to incorporate these conditions dynamically to represent changes in the land surface within a model run, and regional weather models are increasingly incorporating land surface characteristics. Extensive literature, as well as textbooks, document this understanding as do models of land surface processes and properties. A technical input report to the assessment (Loveland et al. 2012) summarizes the literature and basic understanding of interactions between the atmosphere and land surface that influence climate. Many studies establish and characterize these interactions at various spatial and temporal scales through remote sensing and field observations as well as large-scale experiments, including BOREAS and LBA. Examples are provided within the chapter to demonstrate that land use and land-cover change are affecting U.S. climate (Arnfield 2003; Bonan 2001; Fall et al. 2010; Landsberg 1970; Niyogi et al. 2011; Shepherd et al. 2002; Sleeter 2008; Sorooshian et al. 2011; Souch and Grimmond 2006; Yow 2007; Zhu et al. 2011).
New information and remaining uncertainties	While there is little uncertainty about this key message in general, the heterogeneity of the U.S. landscape and associated processes as well as regional and local variations in atmospheric processes make it difficult to analyze or predict the character of land use and land cover influences on atmospheric processes at all scales.
Assessment of confidence based on evidence	**Very High.** The basic processes underlying the biophysics of interactions between the land surface and atmosphere are well understood. A number of examples and field studies are consistent in demonstrating effects of land use and land-cover change on climate of the U.S.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/4	**Individuals, organizations, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.**
Description of evidence base	The key message is supported by well-understood aspects of land use planning and management, including the legal roles of government and citizens and management practices such as zoning and taxation. Participants in the NCA workshop (Nov 29-Dec 1, 2011 in Salt Lake City) on land use and land cover presented and discussed a number of examples showing the influences of land use decisions on climate change adaptation options (Lebow et al. 2012). The chapter describes specific examples of measures to adapt to climate change to further support this key message (ICLEI 2011; ISC 2010; SFBCDC 2011).
New information and remaining uncertainties	Experience with climate change adaptation measures involving land use decisions is accumulating rapidly. Although there is little uncertainty that land use decisions can enable adaptation to climate change, the information about climate change at scales where such decisions are made is generally lacking.
Assessment of confidence based on evidence	**Very High.** The aspects of land-use planning that can enable climate change adaptation are well understood and examples demonstrate where actions are being taken.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #4/4	**Choices about land use and land management provide a means of reducing atmospheric greenhouse gas levels.**
Description of evidence base	The evidence base for this key message includes scientific studies on the carbon cycle at both global and local scales, and policy studies on the costs and benefits, and feasibilities, of various actions to reduce carbon emissions from land-based activities and/or to increase carbon storage in the biosphere through land-based activities. Foundational studies are summarized in the NCA Technical Input documents.
New information and remaining uncertainties	A major study by the USGS is estimating carbon stocks in vegetation and soils of the U.S., and this inventory will clarify the potential for capturing greenhouse gasses by land-use change (An early result is reported in Sohl et al. 2012). There is little uncertainty behind the premise that certain specific land uses affect the carbon cycle. There are, however, scientific uncertainties regarding the magnitudes of effects resulting from specific actions designed to leverage this linkage for mitigation. For example, uncertainties are introduced regarding the permanence of specific land-based stores of carbon, the incremental value of specific management or policy decisions to increase terrestrial carbon stocks beyond changes that would have occurred in the absence of management, and the possibility for decreases in carbon storage in another location to offset increases resulting from specific actions at a given location. Also, we do not yet know how natural processes might alter the amount of carbon storage expected to occur with management actions. There are also uncertainties regarding the political feasibilities and economic efficacy of policy options to use land-based activities to reduce the concentration greenhouse gases in the atmosphere.
Assessment of confidence based on evidence	Given the evidence base and uncertainties there is **medium** confidence that land use and land management choices can reduce the amount of greenhouse gases in the atmosphere.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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14. Rural Communities

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Key Messages

1. **Rural Communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.**
2. **Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increases the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.**
3. **Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.**

Over 95% of U.S. land area is classified as rural, but is home to just 19.3% of the population (USDA 2012; U.S. Census Bureau 2010a, 2010b; HRSA 2012). Rural America's importance to the country's economic and social well-being is disproportionate to its population, however, since rural areas provide natural resources that much of the rest of the U.S. depends on for food, energy, water, forests, recreation, national character, and quality of life (ERS 2003). Rural economic foundations and community cohesion are intricately linked to these natural systems, which are inherently vulnerable to climate change. Urban areas that depend on goods and services from rural areas will also be affected by climate change-driven impacts across the countryside.

Rural Counties

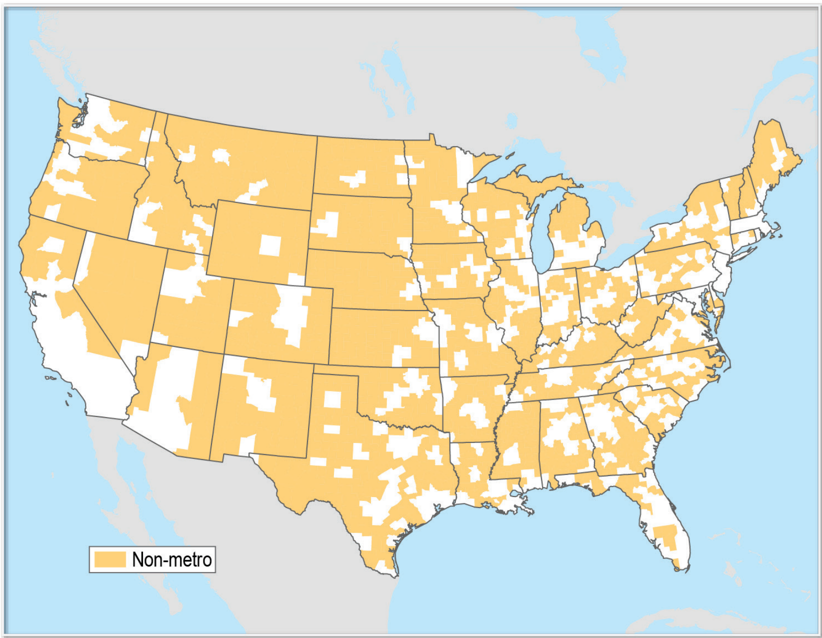

Figure 14.1: Rural Counties

Caption: Although about 80% of the U.S. population lives in urban areas, most of the country is still classified as rural. (Source: USDA Economic Research Service, Atlas of Rural and Small-Town America, 2012; based on data from 2000).

Warming trends, climate volatility, extreme weather events, and environmental change are already affecting the economies and cultures of rural areas. Many rural communities face considerable risk to their infrastructure, livelihoods, and quality of life from observed and projected climate shifts. These changes will progressively increase volatility in food commodity markets, shift the ranges of plant and animal species, and, depending on the region, increase water scarcity, exacerbate flooding and coastal erosion, and increase the intensity and frequency of wildfires across the rural landscape.

Climate changes will severely challenge many rural communities, shifting locations where particular economic activities are capable of thriving. Changes in the timing of seasons, temperatures, and precipitation will alter where commodities, value-added crops, and recreational activities are best suited. Because many rural communities are less diverse than urban areas in their economic activities, changes in the viability of one traditional economic sector will place additional stresses on community stability.

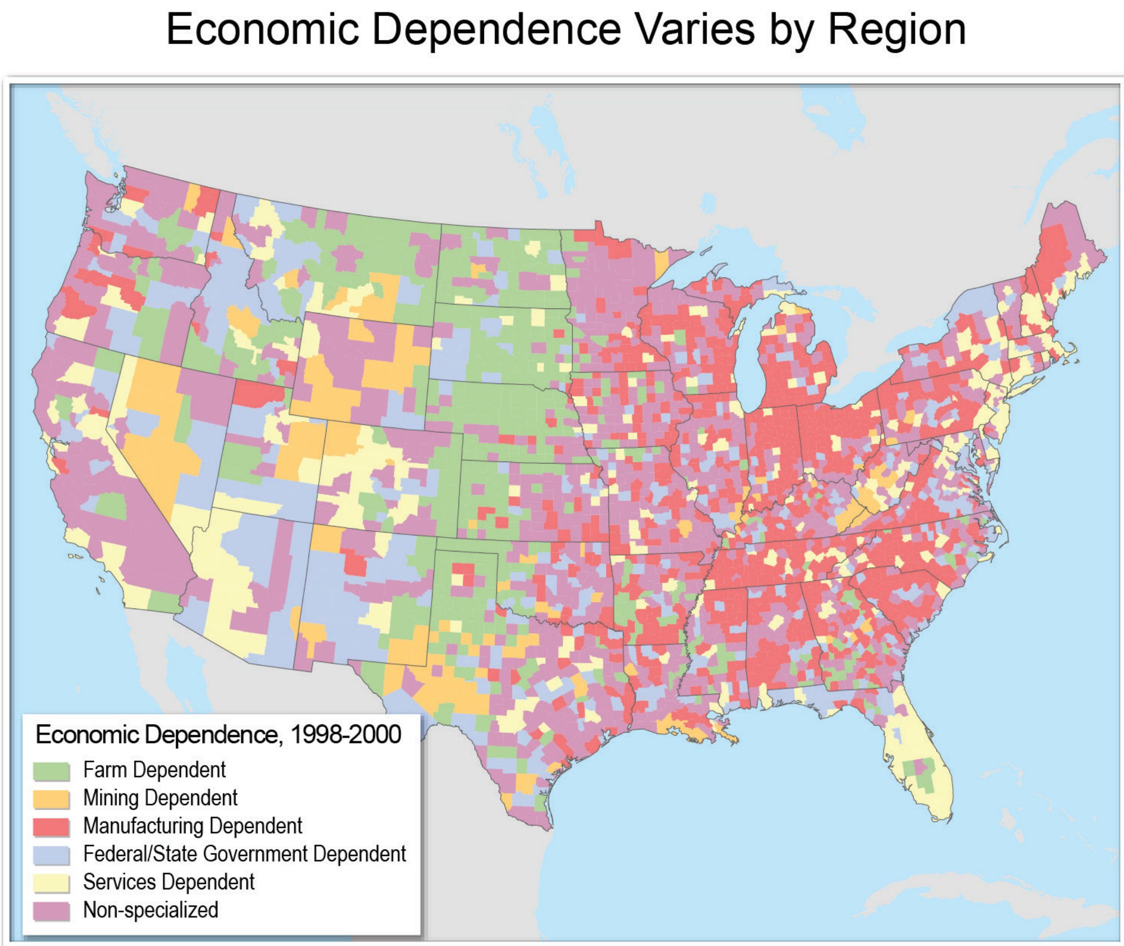

Figure 14.2: Economic Dependence Varies by Region

Caption: Much of the rural U.S. depends on agriculture, mining, and manufacturing. Climate changes will affect each region and each economic sector in complex and interrelated ways. (Source: USDA Economic Research Service, Atlas of Rural and Small-Town America, 2012).

Climate change impacts will not be uniform or consistent across rural areas, and some communities may benefit from climate change. In the short term, the U.S. agricultural system is expected to be fairly resilient to climate change due to the system's flexibility to engage in adaptive behaviors, such as expansion of irrigated acreage, regional shifts in acreage for specific crops, crop rotations, changes to management decisions (such as choice and timing of inputs and cultivation practices), and altered trade patterns compensating for yield changes caused by changing climate patterns (Walthall et al. 2012). Recreation, tourism, and leisure activities in some regions will benefit from shifts in temperature and precipitation.

Negative impacts from projected climate changes, however, will ripple throughout rural America. In lakes and riparian areas, for example, warming is projected to increase the growth of algae and invasive species, particularly in areas already facing water quality impairments (Hansson et al. 2012). Mountain species and cold water fish, such as salmon, are expected to see a decrease in their range size due to warming, while some warm water fish, such as bass, could expand their ranges (Janetos et al. 2008). Alaska, with its reliance on commercial and subsistence fishing catch, is particularly vulnerable. Warmer weather and higher water temperatures will reduce salmon harvests, creating hardships for the rural communities that depend upon these catches (NTAA 2009). Communities in Guam and American Samoa, which depend on fish for 25% to 69% of their protein, are expected to be particularly hard hit, as climate change alters the composition of coral reef ecosystems (Lal et al. 2011).

Across the U.S., rural areas provide ecosystem services – like carbon absorption in forests, water filtration in wetlands, and wildlife habitat in prairies – whose value tends to be overlooked. Preserving these ecosystem services sustains the quality of life in rural communities and also benefits those who come to rural communities for second homes, tourism, and other amenities, while providing urban residents with vital resources – like food, energy and fresh water – that meet essential needs. This layered connection between rural areas and populous urban centers suggests that maintaining the health of rural areas is a national, and not simply a local, concern.

Rural Economies

Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.

Rural America has already experienced some of the impacts of climate change related weather effects, including crop and livestock loss from severe drought and flooding (Peterson et al., 2012), infrastructure damage to levees and roads from extreme storms (DOT 2010), shifting planting and harvesting times in farming communities (Kunkel 2009), and large-scale losses from fires and other weather-related disasters (Westerling et al. 2006). These impacts have profound effects, and are amplified by the essential economic link that many of these communities have to their natural resource base.

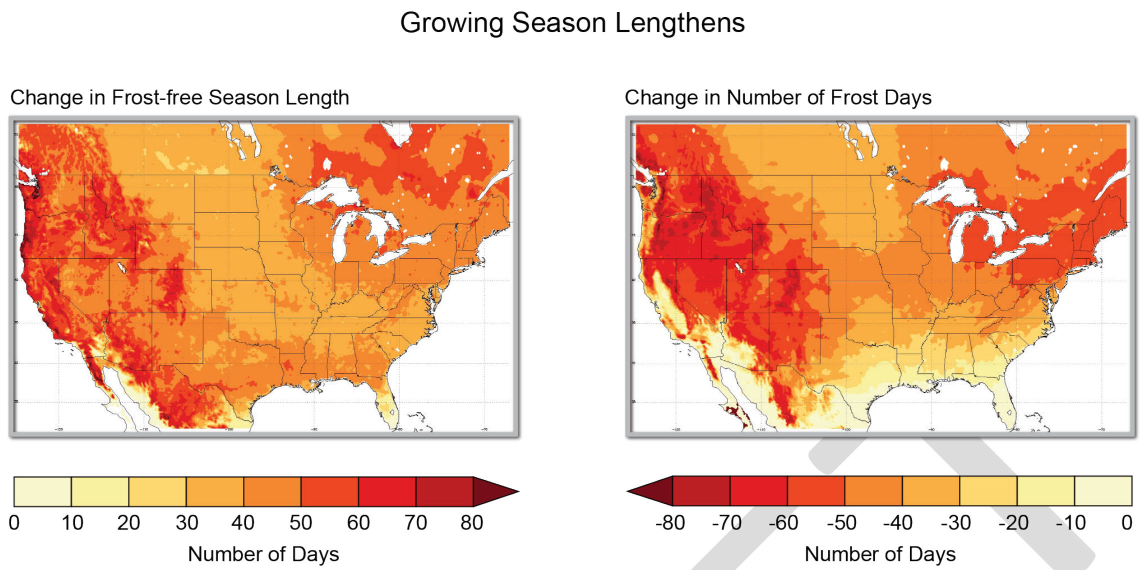

Figure 14.3: Growing Season Lengthens

Caption: The left map shows that if emissions continue to increase (A2 scenario), the U.S. growing season (or frost-free season) will lengthen by as much as 20 to 40 days by the end of the century (2070-2099 as compared to 1971-2000). The right map shows a reduction in the number of frost days (days with minimum temperatures below freezing) by 20 to 60 days in much of the U.S. in the same time period. Reductions in the number of frost days can result in early bud-bursts or blooms, consequently damaging some perennial crops grown in the U.S. (See also Ch. 6: Agriculture). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3.)

Rural communities are often characterized by their natural resources and associated economic activity. Dominant economic drivers include agriculture, forestry, mining, energy, outdoor recreation, and tourism. In addition, many rural areas with pleasant climates and appealing landscapes are increasingly reliant on second-home owners and retirees for their tax base and community activities.

Nationally, fewer than 7% of rural workers are directly employed in agriculture, but the nation's two million farms occupy more than 40% of U.S. land mass – and many rural communities rely extensively on farming and ranching (Brown and Schafft 2011; Ch. 6 Agriculture; Ch. 13 Land Use and Land Cover Change). Ongoing climate changes will continue to shift cropping patterns and timing of planting and harvesting. Changes in rainfall, temperature, and extreme weather events will increase the risk of poor yields and reduced crop profitability. It is projected that increased intensity of extreme weather events (like more intense rainfall events and more frequent heat waves) will accelerate soil erosion rates, increasing deposition of nitrogen and phosphorous into water bodies, and diminished water quality (Delgado et al. 2011).

Many areas will face increasing competition for water among household, industrial, agricultural and urban users (Iverson et al. 2008; Ch. 3 Water Resources). While irrigated cropland is an important and growing component of the farm economy (NRC 2010), water withdrawals necessary for generation of electricity in thermal power plants are already roughly equal to irrigation withdrawals (Hutson 2004). As climate change increases water scarcity in some regions, demand for water for both energy production and agriculture will increase (CCSP 2008; Wilbanks et al. 2008). Mining also requires large quantities of water, and water scarcity resulting from drought associated with climate change may affect operations. Changes in seasonality and intensity of precipitation will increase costs of runoff containment.

Climate change impacts on forestry have important implications for timber and forest amenity-based rural communities. Shifting forest range and composition, as well as increased attacks from pests and diseases, will have negative effects on biodiversity and will increase wildfire risks (Lal et al. 2011; Negron et al. 2009; Ch. 7 Forestry). Shifts in the distribution and abundance of many economically important tree species would affect the pulp and wood industry. As ranges shift and the species composition of forests change, dependent species will also change, causing additional economic and socio-cultural impacts.

Tourism contributes significantly to rural economies. Changes in the length and timing of seasons, temperature, precipitation, and severe weather events can have a direct impact on tourism and recreation activities by influencing visitation patterns and tourism-related economic activity.

Climate change impacts on tourism and recreation will vary significantly according to region. For instance, some of Florida's top tourist attractions, including the Everglades and Florida Keys, are threatened by sea level rise (Stanton and Ackerman 2007), with estimated loss of revenue that could total $9 billion by 2025 and $40 billion by the 2050s. The effects of climate change on the tourism industry will not be exclusively negative. In Maine, coastal tourism could increase due to warmer summer months, with more people visiting the state's beaches (Burkett and Davidson 2012). Employing a Tourism Climatic Index that accounts for temperature, precipitation, sunshine, and wind, one study finds that conditions conducive for outdoor recreation will be shifting northward with climate change, though it is unclear whether absolute conditions or relative weather conditions will be more important in influencing future tourist behaviors (Amelung et al. 2007).

Climate-Change Impacts on Summertime Tourism

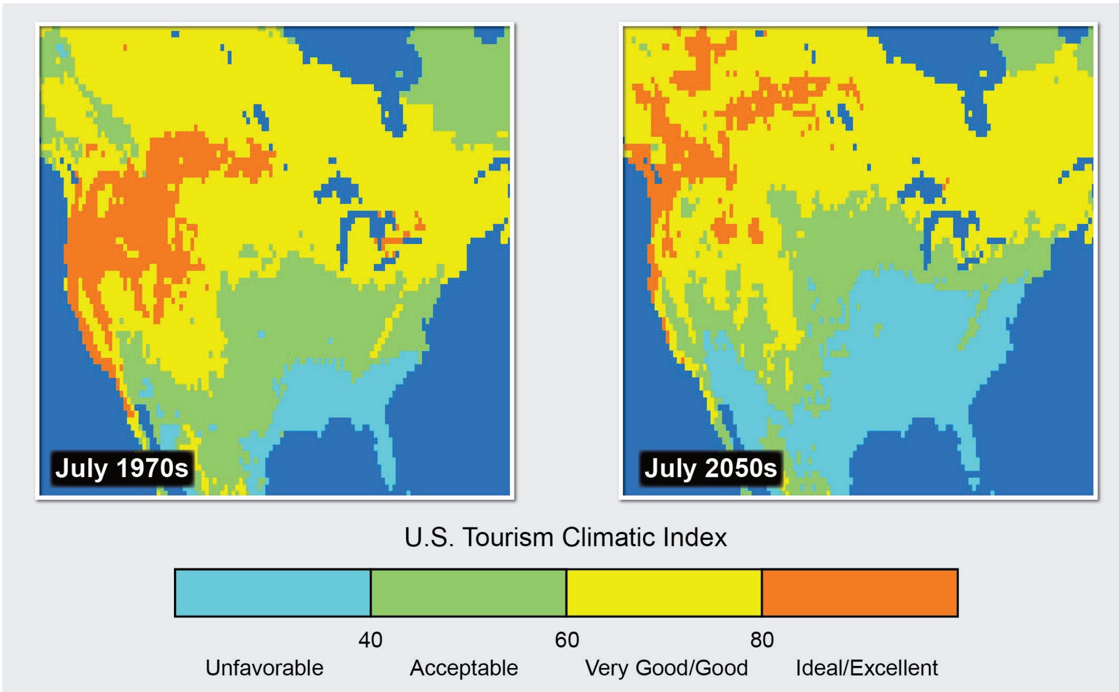

Figure 14.4: Climate-Change Impacts on Summertime Tourism

Caption: Tourism is often climate-dependent as well as seasonally-dependent. Increasing heat and humidity projected for summers in the Midwest, Southeast, and parts of the Southwest region by mid-century (compared to the period 1961-1990) is likely to create unfavorable conditions for summertime outdoor recreation and tourism activity. The figures illustrate projected changes in climatic attractiveness (based on maximum daily temperature and minimum daily relative humidity, mean daily temperature and mean daily relative humidity, precipitation, sunshine, and wind speed) in July for much of North America. In the coming century, the distribution of these conditions is projected to shift from acceptable to unfavorable across most of the Southeast and southern Midwest region, and from very good or good to acceptable conditions in the northern portions of the Midwest. (Figure source: Nicholls et al. 2005).

Climate change will also influence the distribution and composition of plants and animals across the U.S. Hunting, fishing, bird watching, and other wildlife-related activities will be affected as habitats shift and relationships among species change (Allen et al. 2009; Carter et al. 2012). Cold-weather recreation and tourism will be adversely affected by climate change. Snow accumulation in the western U.S. has decreased, and is expected to continue to decrease, as a result of observed and projected warming. Reduced snow accumulation also reduces the amount of spring snowmelt, decreasing warm-season runoff in mid- to high-latitude regions.

Similar changes to snowpack are expected in the Northeast U.S. (Bales et al. 2012). Adverse impacts on winter sports are projected to be more pronounced in the Northeast and Southwest regions of the U.S. (Lal et al. 2011). Coastal areas will be adversely affected by sea level rise and increased severity of storms (Hoyos et al. 2006; Kleinosky et al. 2006; Wu et al. 2002). Changing environmental conditions, such as wetland loss and beach erosion in coastal areas (Galgano and Douglas 2000) and increased risk of natural hazards such as wildfire, flash flooding, storm surge, river flooding, drought, and extremely high temperatures can alter the character and attraction of rural areas as tourist destinations.

The implications of climate change on communities that are dependent on resource extraction (coal, oil, natural gas, and mining) have not been well studied. Attributes of economic development in these communities, such as cyclical growth, transient workforce, rapid development, pressure on infrastructure, and lack of economic diversification suggest that these communities could face challenges in adapting to climate change (Austin 2006; Brown and Schafft 2011; Krannich 2012; Stedman et al. 2011).

Responding to Risks

Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population increases the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.

Relatively rapid changes in demographics, economic activity, and climate are particularly challenging in rural communities, where local, agrarian values often run generations deep. Changing rural demographics, influenced by new immigration patterns, fluctuating economic conditions, and evolving community values add to these challenges – especially with regard to climate changes.

Modern rural populations are generally older, less affluent, and less educated than their urban counterparts. Rural areas are characterized by higher unemployment, more dependence on government transfer payments, less diversified economies, and fewer social and economic resources needed for resilience in the face of major changes (Isserman et al. 2009; Lal et al. 2011). In particular, the combination of an aging population and poverty increases the vulnerability of rural communities to climate fluctuations.

Many Rural Areas are Losing Population

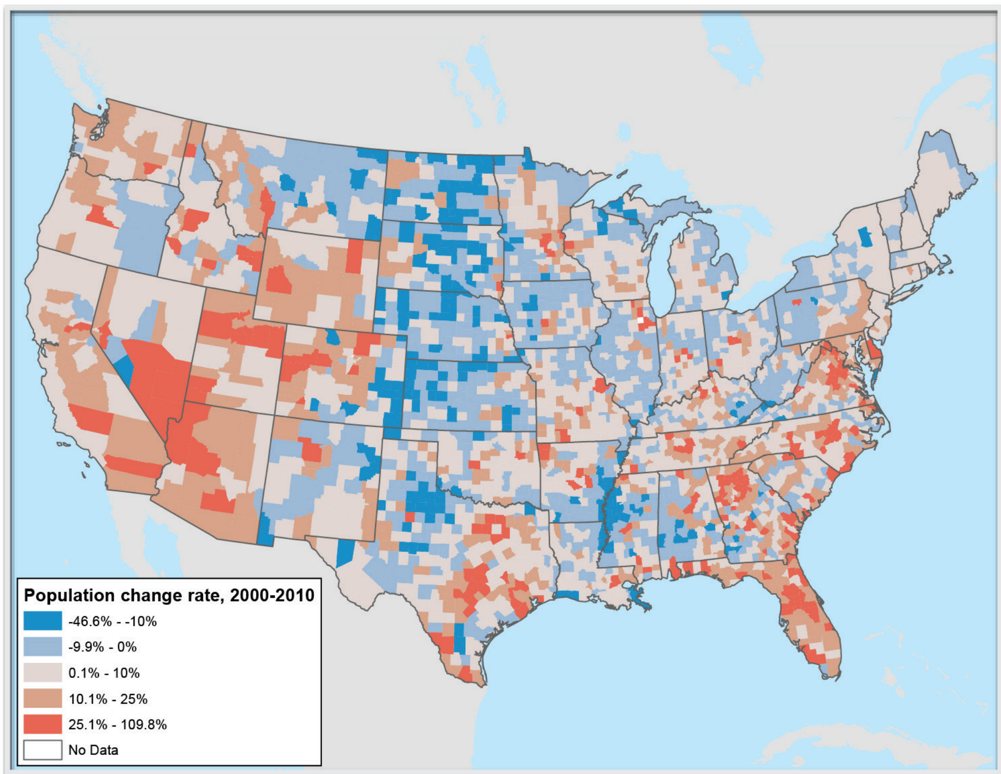

Figure 14.5: Many Rural Areas are Losing Population

Caption: Census data show significant population declines in many rural areas, notably in the Great Plains. Many rural communities' existing vulnerabilities to climate change, including physical isolation, reduced services like health care, and an aging population, are projected to increase as population decreases. (Data from U.S. Census Bureau 2010a; Figure Source: USDA Economic Research Service, Atlas of Rural and Small-Town America 2012).

There has been a trend away from manufacturing, resource extraction, and farming to amenity-based economic activity in many rural areas of the United States (English et al. 2000; Green 2001; Kim et al. 2005). Expanding amenity-based economic activities in rural areas include recreation and leisure, e-commuting residents, tourism, and second home and retirement home development. This shift has stressed traditional cultural values (Green et al. 1996) and put pressure on infrastructure (Reeder and Brown 2005) and natural amenities (Cohen 1978) that draw people to rural areas. Changes in climate and weather are likely to increase these stresses. Rural components of transportation systems are particularly vulnerable to risks from flooding and sea level rise (Gill et al. 2009). Since rural areas often have fewer transportation options and fewer infrastructure redundancies, any disruptions in road, rail, or air transport will deeply affect rural communities.

Rural communities rely on various transportation modes, both for export and import of critical goods (Ch. 5: Transportation). Climate changes will result in increased erosion and maintenance costs for local road and rail systems, as well as changes in streamflows and predictability that will result in increased maintenance costs for waterways. More frequent disruption of shipping is projected, with serious economic consequences. For example, in 2010, about 40 million tons of cereal grains were shipped by water to Louisiana, while less than 4 million tons traveled by rail (DOT 2010). While rail can help ameliorate small-scale or off-peak capacity limitations on the Mississippi River, it seems unlikely that the rail system can fully replace the river system in the event of a prolonged harvest-time disruption. Events that affect both rail and barge traffic would be particularly damaging to rural communities that depend upon these systems to get commodities to market.

Health and emergency response systems also face additional demands from substantial direct and indirect health risks associated with global climate changes. Indirect risks, particularly those posed by emerging and re-emerging infectious diseases, are more difficult to assess, but pose looming threats to economically challenged communities where health services are limited. Direct threats (such as extreme heat and storm events, coastal and riparian flooding) tend to be more associated with specific local vulnerabilities, and the risk somewhat easier to assess (Setlow et al. 1996)

The socioeconomic and demographic characteristics of rural areas interact with climate change to create health concerns that differ from those of urban and suburban communities. Older populations with lower income and educational levels in rural areas spend a larger proportion of their income on health care than their urban counterparts. Moreover, health care access declines as geographic isolation increases. Overall, rural residents already have higher rates of age-adjusted mortality, disability, and chronic disease than do urban populations (Jones et al. 2009). These trends are likely to be exacerbated by climate change (Ch. 9: Human Health).

Governments in rural areas are generally ill-prepared to respond quickly and effectively to large-scale events, although individuals and voluntary associations often show significant resilience. Health risks are exacerbated by limitations in the health service systems characteristic of rural areas, including the distance between rural residents and health care providers and the reduced availability of medical specialists.

The effects of climate change on mental health merit special consideration. Rural residents are already at a heightened risk from mental health issues because of the lack of access to mental health providers. The adverse impact of severe weather disasters on mental health is well established (Salcioglu et al. 2007), and there is emerging evidence that climate change in the form of increasing heat waves and droughts has harmful effects on mental health. Droughts often result in people relocating to seek other employment, causing a loss of home and social networks. Studies have shown that spring droughts in rural areas cause a decrease in life satisfaction (Hart et al. 2011). Primary care physicians who form the backbone of rural health care often have insufficient training in mental health issues, as well as heavy caseloads and a lack of specialized training or backup (Jones et al. 2009).

The frequency and distribution of infectious diseases is also projected to increase with rising temperatures and associated seasonal shifts. Increased rates of mutation and increased resistance to drugs and other treatments are already evident in the behavior of infectious disease-causing bacteria and viruses (Alanis 2005). In addition, changes in temperature, surface water, humidity, and precipitation affect the distribution and abundance of disease-carriers and intermediate hosts, and result in larger distributions for many parasites and diseases. Rural residents who spend significant time outdoors have an increased risk to being exposed to these disease-carriers, like ticks and mosquitoes (Ch. 9: Human Health).

Adaptation

Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.

Climate variability and increases in temperature, extreme events (storms, flooding, heat waves, droughts), and sea level rise are expected to have widespread impact on the provision of services from local, regional, and state governments. Emergency management, energy use and distribution systems, transportation and infrastructure planning, and public health will all be affected.

Rural governments often depend heavily on volunteers to meet community challenges like fire protection or flood response. In addition, rural communities have limited locally available financial resources to help deal with the effects of climate change. Small community size tends to make services expensive or available only by traveling some distance.

Local governance structures tend to de-emphasize planning capacity, compared to urban areas. While 73% of metropolitan counties have land-use planners, only 29% of rural counties not adjacent to a metropolitan county had one or more planners. Moreover, rural communities are not equipped to deal with major infrastructure expenses (Kraybill and Lobao 2001).

Communities across the U.S. are experiencing infrastructure losses, water scarcity, unpredictable water availability, and increased frequency and intensity of wildfires. However, these observed changes are often not explicitly associated with climate change by local authorities, and responses rarely take climate disruption into account. Even in communities where there is increasing awareness of climate change and interest in comprehensive adaptation planning, lack of funding, human resources, and access to information, training, and expertise provide significant barriers for many rural communities.

To respond adequately to future climate changes, rural communities will need help assessing their risks and vulnerabilities, prioritizing and coordinating projects, funding and allocating financial and human resources, and deploying information-sharing and decision support tools.

Impacts due to climate change will interact across communities and regions, making solutions dependent upon meaningful participation of numerous stakeholders from federal, state and local governments, science and academia, the private sector, non-profits, and the general public.

Effective adaptation measures are closely tied to specific local conditions and needs and take into account existing social networks (Berkes 2007; Nelson 2011; Ostrom 2009). The economic and social diversity of rural communities affects the ability of both individuals and communities to adapt to climate changes, and underscores the need to assess climate change impacts on a local basis. The quality and availability of natural resources, legacies of past use, and changing industrial needs affect the economic, environmental, and social conditions of rural places and are critical factors to be assessed (Adger and Nelson 2010; Bark and Jacobs 2009; Brown and Schafft 2011; Flora 2001; Oliver-Smith 2006; Peacock and Girard 1997; Peguero 2006; Stedman et al. 2011; Vásquez-León 2009). Successful adaptation to climate change requires balancing immediate needs with long-term development goals, as well as development of local-level capacities to deal with climate change (Furman et al. 2011; Nelson 2011; O'Brien 2009).

Potential national climate change mitigation responses, especially those that require extensive use of land – permanent reforestation, constructing large solar or wind arrays, hydroelectric generation, and biofuel cropping – are also likely to significantly affect rural communities. As with the development of rural resource-intensive economic activities, where national or multi-national companies tend to wield ownership and control, local residents and communities are unlikely to be the primary investors or beneficiaries of this kind of new economic activity.

Decisions regarding adaptation responses for both urban and rural populations can occur at various scales (federal, state, local, private sector, individual) but need to take interdependencies into account. Some decisions may not be under the control of local governments or rural residents. Given that timing is a critical aspect of adaptation, engaging rural residents early in decision processes about investments in public infrastructure, protection of shorelines, changes in insurance provision, or new management initiatives can influence individual behavior and choice in ways that enhance adaptation.

Box: Local Responses to Climate Change in the San Juan Mountains

The San Juan Mountains region straddles the southern edge of the Southern Rocky Mountains and the northeastern tip of the arid Southwest. The high mountain headwaters of the Rio Grande, San Juan, and major tributaries of the Upper Colorado River are critical water towers for six states: Texas, Nevada, California, Arizona, and New Mexico. The diversity of the landforms, high plateaus, steep mountains, deep canyons, and foothills leads to a complex and diverse mix of coniferous and deciduous forested landscapes (Romme et al. 2009). Counties in the area range from 700 to 51,000 people, with population changes between 2000 and 2010 ranging from a 25% decline to an 86% increase. Public lands account for 69% of the land base (U.S. Forest Service 2008). Over half of the local economies are dependent upon natural resources to support tourism, minerals and natural gas extraction, and second home development.

Average annual temperatures in the San Juan Mountains have risen 1.1ºF in only three decades (Rangwala and Miller 2010), a rate of warming greater than any other region of the U.S. except Alaska (Ray et al. 2008). The timing of snowmelt has shifted two weeks earlier, and this earlier seasonal release of water resources is of particular concern to all western states (Clow 2010). Current challenges for the region include changes in forests due to pests and diseases, intensive recreation use, fire management for natural and prescribed fires, and increasing development in the wildland-urban interface. Communities are vulnerable to changes from a warmer and drier climate that would affect frequency and intensity of wildfires, shift vegetation and range of forest types, and increase pressures on water supplies.

In response, the San Juan Climate Initiative drew together stakeholders, including natural resource managers, community planners, elected officials, industry, resource users, citizens, non-profit organizations, and scientists. By combining resources and capabilities, stakeholders have been able to accomplish much more together than if they had worked independently. For example, local governments developed a plan to reduce greenhouse gas emissions and identify strategies for adaptation, signing the U.S. Mayor's Climate Protection Agreement in 2009. Climate modelers at University of Colorado and National Center for Atmospheric Research analyzed regional trends in temperature, precipitation, snowpack, and streamflow. Researchers at Mountain Studies Institute, University of Colorado, and Fort Lewis College are partnering with San Juan National Forest to monitor alpine plant communities and changes in climate across the region, and to document carbon resources. San Juan National Forest is developing strategies for adapting to climate changes in the region related to drought, wildfire, and other potential effects. La Plata County is leading an effort to plan for sustainable transportation and food networks that will be less dependent upon carbon-based fuels, while the Mountain Studies Institute is leading citizen science programs to monitor changes to sensitive species like the American pika.

-- end box --

Traceable Accounts

Chapter 14: Rural Communities

Key Message Process: The key messages were initially developed at a meeting of the authors in Charleston, South Carolina, in February, 2012. This initial discussion was supported by a series of conference calls from March through June, 2012. These ensuing discussions were held after a thorough review of the technical inputs and associated literature, including the Rural Communities Workshop Report prepared for the NCA (Hauser and Jadin 2012) and additional technical inputs on a variety of topics.

Key message #1/3	Rural Communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the rural communities' workshop report (Hauser and Jadin 2012), and 31 technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence that the impacts of climate change are increasing is compelling and widespread. This evidence is based on historical records and observations and on GCMs, including those driven by B1 (substantial emissions reduction) and A2 (continued increases in global emissions) Scenarios. This evidence is clearly summarized and persuasively referenced in the "Our Changing Climate" chapter of this Assessment and in the Scenarios developed for the NCA by Kunkel et al. Work done by Brown et al. (Brown and Schafft 2011) has demonstrated the dependency of rural communities on their natural resources, with a number of studies showing that climate change results in crop and livestock loss (Peterson et al. 2012), infrastructure damage to levees and roads (DOT 2010), shifts in agriculture practices (Kunkel 2009), and losses due to disasters (Westerling et al. 2006). A number of publications project these impacts to increase, with effects to the natural environment (Delgado et al. 2011; Lal et al. 2011; Negron et al. 2009) and increased competition for water between agriculture and energy (CCSP 2008; Wilbanks et al. 2008). Studies have projected tourism locations in the Everglades and Florida Keys are threatened (Stanton and Ackerman 2007) while Maine's tourism could increase (Burkett and Davidson 2012), which coincides with a projected northern shift of outdoor recreation (Amelung et al. 2007). Additionally, beach erosion and wetland loss (Galgano and Douglas 2000), plant and animal habitats, and inter-species relationships will change, affecting hunting, fishing, and bird watching (Karl et al. 2009), and many areas are affected by early snowpack melt (Bales et al. 2012; Lal et al. 2011), while all effect outdoor recreation and tourism in the U.S.
New information and remaining uncertainties	Key remaining uncertainties relate to precise magnitude, timing, and location at regional and local scales.
Assessment of confidence based on evidence	Given the evidence and uncertainties, there is **very high** confidence that rural communities are highly dependent on natural resources that are expected to be affected by climate change, especially the many communities that rely on farming, forestry or tourism for their likelihoods. Given the evidence and uncertainties, there is **high** confidence that climate change

	is currently affecting rural communities. There is **very high** confidence that impacts will increase, as evidenced by climate science chapter of this assessment given the evidence and uncertainties

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 14: Rural Communities

Key Message Process: See Key Message #1

Key message #2/3	**Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population increases the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the rural communities' workshop report (Hauser and Jadin 2012) and 31 technical input reports on a wide range of topics that were also received and reviewed as part of the Federal Register Notice solicitation for public input. With studies showing that rural communities are already stressed (Cohen 1978; Green et al. 1996; Reeder and Brown 2005), a number of publications have explored the barriers of rural communities to preparing and responding to climate change (Isserman et al. 2009; Lal et al. 2011), with some studies providing in-depth looks at the obstacles that limited economic diversity (English et al. 2000; Green 2001; Kim et al. 2005) and an aging population (Jones et al. 2009) create.
New information and remaining uncertainties	Projecting the interactions of these variables on each other and applying this analysis to local or regional realities is complex at best, with uncertainties at every level of analysis.
Assessment of confidence based on evidence	Given the evidence and uncertainties, there is **high** confidence that the obstacle of physical isolation will hamper some communities' ability to adapt or have an adequate response during extreme events. Given the evidence and uncertainties, there is **high** confidence that the obstacle of limited economic diversity will hinder rural communities' ability to adapt. Given the evidence and uncertainties, there is **high** confidence that the obstacle of higher poverty rates will prevent some communities from adapting properly Given the evidence and uncertainties, there is **high** confidence that the obstacle of an aging population will hinder some rural communities and prevent them from having an adequate response. Given the evidence and uncertainties, there is **high** confidence that fundamental systems in rural communities are already stressed by remoteness and limited access

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 14: Rural Communities

Key Message Process: See Key Message #1

Key message #3/3	**Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the rural communities' workshop report (Hauser and Jadin 2012), and 31 technical input reports on a wide range of topics that were also received and reviewed as part of the Federal Register Notice solicitation for public input. Kraybill and Lobao (Kraybill and Lobao 2001) note that rural communities are not equipped to deal with major infrastructure expenses. Work has been performed illustrating the need to tie adaptation measures to specific local conditions and needs and take into account existing social networks (Berkes 2007; Nelson 2011; Ostrom 2009). Publications have shown that there are a number of critical factors to be assessed, including the quality and availability of natural resources, legacies of past use, and changing industrial needs that effect economic, environmental, and social conditions (Adger and Nelson 2010; Bark and Jacobs 2009; Brown and Schafft 2011; Flora 2001; Oliver-Smith 2006; Peacock and Girard 1997; Peguero 2006; Stedman et al. 2011; Vásquez-León 2009). Additionally, studies have expressed the requirement of accounting for both near- and long-term needs in order for climate change adaptation to be successful (Furman et al. 2011; O'Brien 2009) (Nelson et al. 2007).
New information and remaining uncertainties	It is difficult to fully capture the complex interactions of the entire socio-economic-ecological system within which the effects of climate change will interact, especially in regard to local and regional impacts. Impact assessments and adaptation strategies require improved understanding of capacity and resilience at every level, international to local. The policy context in which individuals and communities will react to climate effects is vague and uncertain. Identification of informational needs alone indicates that adaptation will be expensive.
Assessment of confidence based on evidence	Given the evidence and uncertainties, there is **high** confidence that rural communities have limited capacity to respond to impacts, because of their remoteness, age, lack of diversity, and all the other reasons listed previously. Given the evidence and uncertainties, there is **high** confidence that rural communities have limited capacity to plan for impacts because of all of the reasons cited earlier. Given the evidence and uncertainties, there is **high** confidence that rural communities will have limited capacity to anticipate impacts because of the lack of infrastructure and expertise available in rural communities. Given the evidence and uncertainties, there is **high** confidence that significant climate change adaptation is needed for transportation in rural communities, especially those in low lying coastal areas. Given the evidence and uncertainties, there is **high** confidence that significant climate change adaptation is needed for health care and emergency response in rural communities, so that rural communities can handle extreme weather events.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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15. Interactions of Climate Change and Biogeochemical Cycles

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Key messages

1. **Human activities have increased CO_2 by more than 30% over background levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends are seen for phosphorus, sulfur, and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
2. **Net uptake of CO_2 by ecosystems of North America captures CO_2 mass equivalent to only a fraction of fossil-fuel CO_2 emissions, with forests accounting for most of the uptake (7-24%, with a best estimate of 13%). The cooling effect of this carbon "sink" partially offsets warming from emissions of other greenhouse gases.**
3. **Major biogeochemical cycles and climate change are inextricably linked, increasing the impacts of climate change on the one hand and providing a variety of ways to limit climate change on the other.**

Introduction

Biogeochemical cycles involve the fluxes of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to sea, from soils to plants. They are called "cycles" because matter is always conserved, although some elements are stored in locations or in forms that are differentially accessible to living things. Human activities have mobilized Earth elements and accelerated their cycles – for example, more than doubling the amount of reactive nitrogen (Nr) that has been added to the biosphere since pre-industrial times (Galloway et al. 2008; Vitousek et al. 1997). (Reactive nitrogen is any nitrogen compound that is biologically, chemically, or radiatively active, like nitrous oxide and ammonia but not nitrogen gas (N_2).) Global-scale alterations of biogeochemical cycles are occurring, from activities both in the U.S. and elsewhere, with impacts and implications now and into the future.

Global CO_2 emissions are the most significant driver of human-caused climate change. But human-accelerated cycles of other elements, especially nitrogen, phosphorus, and sulfur, also influence climate. These elements can act affect climate directly or act as indirect factors that alter the carbon cycle, amplifying or reducing the impacts of climate change.

Climate change is having, and will continue to have, impacts on biogeochemical cycles, which will alter future impacts on climate and affect society's capacity to cope with coupled changes in climate, biogeochemistry, and other factors.

Human-induced Changes

Human activities have increased CO_2 by more than 30% over background levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends are seen for phosphorus, sulfur, and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

The human mobilization of carbon, nitrogen, sulfur, and phosphorus from the Earth's crust has increased 36, 9, 2, and 13 times, respectively, over pre-industrial times (Schlesinger and Bernhardt 2013). Fossil-fuel burning, land-cover change, cement production, and the extraction and production of fertilizer to support agriculture are major causes of these increases (Suddick and Davidson 2012). CO_2 is the most abundant of the greenhouse gases that are increasing due to human activities, and its production dominates atmospheric forcing of global climate change (IPCC 2007). However, methane (CH_4) and nitrous oxide (N_2O) have higher greenhouse capacity per molecule than CO_2, and both are also increasing in the atmosphere. In the U.S. and Europe, sulfur emissions have declined over the past three decades, especially since the mid 1990s, in part because of clean-air legislation to reduce air pollution (Shannon 1999; Stern 2005). Changes in biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, and other elements – and the coupling of those cycles – can influence climate. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight (for example, by creating particles known as aerosols that can reflect sunlight).

State of the carbon cycle

The U.S. was the world's largest producer of human-caused CO_2 emissions from 1950 until 2007, when China surpassed the U.S. Emissions from the U.S. account for 85% of North American emissions of CO_2 (King et al. 2012). Ecosystems represent potential "sinks" for CO_2, which are places where carbon can be stored over the short or long term (see "U.S. Carbon Sink" box). At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades (Woodbury et al. 2007), due to recovery of forests from past disturbances, net increases in forest area, and faster growth driven by climate or fertilization by CO_2 and nitrogen (King et al. 2012; Williams et al. 2012). However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere (King et al. 2012) by a substantial margin.

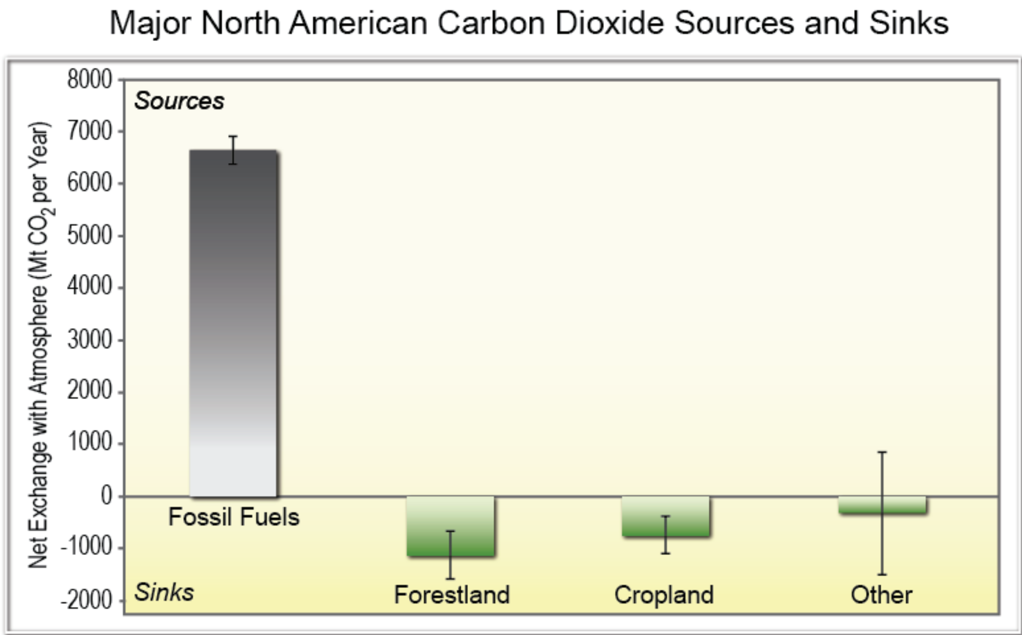

Figure 15.1: Major North American Carbon Dioxide Sources and Sinks

Caption: The release of carbon dioxide from fossil fuel burning in North America (shown here for 2010) vastly exceeds the amount that is taken up and stored in forests, crops, and other ecosystems ("sinks"; shown here for 2000-2006). (Source: Post et al. 2012)

Sources and fates of reactive nitrogen

The nitrogen cycle has been dramatically altered by human activity, especially fertilization, which has increased agricultural production over the past half century (Galloway et al. 2008; Vitousek et al. 1997). Although fertilizer nitrogen inputs have begun to level off in the U.S. since 1980 (U. S. Geological Survey 2010), human-caused reactive nitrogen inputs are now five times greater than those from natural sources (EPA 2011a; Houlton et al. 2012; Suddick and Davidson 2012).

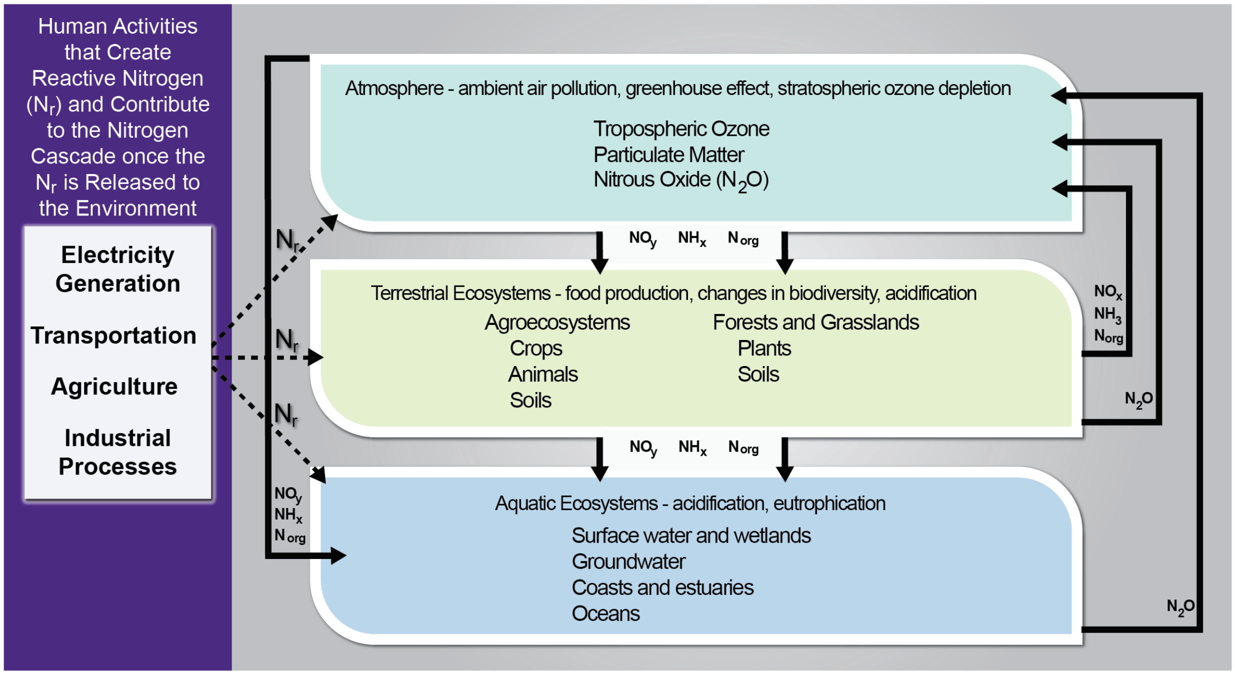

Figure 15.2: Human Activities that Form Reactive Nitrogen and Resulting Consequences in Environmental Reservoirs

Caption: Once created, a molecule of reactive nitrogen has a cascading impact on people and ecosystems as it contributes to a number of environmental issues. (Figure adapted from EPA 2011a; Galloway et al. 2003, with input from USDA). (USDA contributors were Adam Chambers and Margaret Walsh.)

An important characteristic of reactive nitrogen is its legacy. Once created, it can, in sequence, travel throughout the environment (for example, from land to rivers to coasts, sometimes via the atmosphere), contributing to environmental problems such as the formation of coastal low-oxygen "dead zones" in marine ecosystems in summer. These problems persist until the reactive nitrogen is either captured and stored in a long-term pool, like the mineral layers of soil or deep ocean sediments, or converted back to nitrogen gas (N_2) (Baron et al. 2012; Galloway et al. 2003). The nitrogen cycle affects atmospheric concentrations of the three most important human-caused greenhouse gases: carbon dioxide, methane, and nitrous oxide.

Phosphorus and other elements

In the U.S., the phosphorus cycle has been greatly transformed, (MacDonald et al. 2011; Smil 2000) primarily from the use of phosphorus in agriculture. Phosphorus has no direct effects on climate, but rather, an indirect effect: increasing carbon sinks by fertilization of plants.

Carbon Sinks

Net uptake of CO_2 by ecosystems of North America captures CO_2 mass equivalent to only a fraction of fossil-fuel CO_2 emissions, with forests accounting for most of the uptake (7-24%, with a best estimate of 13%). The cooling effect of this carbon "sink" partially offsets warming from emissions of other greenhouse gases.

Considering CO_2 concentration, the sink on land is small compared to the source: more CO_2 is emitted than can be taken up (EPA 2012; Hayes et al. 2012; King et al. 2012; Pacala et al. 2007) (see "U.S. Carbon Sink" box). Other elements and compounds affect that balance by direct and indirect means. The net effect on Earth's radiative balance from changes in major biogeochemical cycles (carbon, nitrogen, sulfur, and phosphorus) depends upon processes that directly affect how the planet absorbs or reflects sunlight, as well as those that indirectly affect concentrations of greenhouse gases in the atmosphere.

Carbon

In addition to the CO_2 effects described above, other carbon-containing compounds affect climate change (like methane [CH_4] and volatile organic compounds [VOCs]). Methane is the most abundant non-CO_2 greenhouse gas, with atmospheric concentrations that are now more than twice those of pre-industrial times (Bousquet et al. 2006; Montzka et al. 2011).

Methane has direct radiative effects on climate because it traps heat, and indirect effects on climate because of its influences on atmospheric chemistry. An increase in methane concentration in the industrial era has contributed to warming in many ways (Forster et al. 2007). Increases in atmospheric methane, VOCs, and nitrogen oxides (NOx) are expected to deplete concentrations of hydroxyl radicals, causing methane to persist in the atmosphere and exert its warming effect for longer periods (Montzka et al. 2011; Prinn et al. 2005). The hydroxyl radical is the most important "cleaning agent" of the troposphere, where it is formed by a complex series of reactions involving ozone and ultraviolet light (Schlesinger and Bernhardt 2013).

Nitrogen and Phosphorus

The climate effects of an altered nitrogen cycle are substantial and complex (Pinder et al. 2012; Post et al. 2012; Suddick and Davidson 2012). CO_2, methane, and nitrous oxide contribute most of the anthropogenic (human-caused) increase in climate forcing, and the nitrogen cycle affects atmospheric concentrations of all three gases. Nitrogen cycling processes regulate ozone (O_3) concentrations in the troposphere and stratosphere, and produce atmospheric aerosols, all of which have additional direct effects on climate. Excess reactive nitrogen also has multiple indirect effects that simultaneously amplify and mitigate changes in climate.

The strongest direct effect of an altered nitrogen cycle is through emissions of nitrous oxide (N_2O), a long-lived and potent greenhouse gas that is increasing steadily in the atmosphere (Forster et al. 2007; Montzka et al. 2011). Globally, agriculture has accounted for most of the atmospheric rise in N_2O (Matson et al. 1998; Robertson et al. 2000). Roughly 60% of agricultural N_2O derives from high soil emissions that are caused by nitrogen fertilizer use. Animal waste treatment and crop-residue burning account for about 30% and about 10%, respectively (Robertson 2004). The U.S. reflects this global trend: around 75% to 80% of U.S. human-caused N_2O emissions are due to agricultural activities, with the majority being emissions from fertilized soil. The remaining 20% is derived from a variety of industrial and energy sectors (Cavigelli et al. 2012; EPA 2011b). While N_2O currently accounts for about 6% of human-caused warming (Forster et al. 2007), its long lifetime in the atmosphere and rising concentrations will increase N_2O-based climate forcing over a 100-year time scale (Davidson 2012; Prinn 2004; Robertson and Vitousek 2009; Robertson et al. 2012).

Excess reactive nitrogen indirectly exacerbates changes in climate by several mechanisms. Emissions of nitrogen oxides (NO_x) increase the production of tropospheric ozone, which is a greenhouse gas (Derwent et al. 2008). Elevated tropospheric ozone may reduce CO_2 uptake by plants and thereby reduce the terrestrial CO_2 sink (Long et al. 2006; Sitch et al. 2007). Nitrogen deposition to ecosystems can also stimulate the release of nitrous oxide and methane and decrease methane uptake by soil microbes (Liu and Greaver 2009).

Excess reactive nitrogen mitigates changes in greenhouse gas concentrations and climate through several intersecting pathways. Over short time scales, NO_x and ammonia emissions lead to the formation of atmospheric aerosols, which cool the climate by scattering or absorbing incoming radiation and by affecting cloud cover (Forster et al. 2007; Leibensperger et al. 2012). In addition, the presence of NO_x in the lower atmosphere increases the formation of sulfate and organic aerosols (Shindell et al. 2009). At longer time scales, NO_x can increase rates of methane oxidation, thereby reducing the lifetime of this important greenhouse gas.

One of the dominant effects of reactive nitrogen on climate stems from how it interacts with ecosystem carbon capture and storage (sequestration) and thus, the carbon sink. As mentioned previously, addition of reactive nitrogen to natural ecosystems can increase carbon sequestration as long as other factors are not limiting plant growth, such as water availability and other nutrients (Melillo et al. 2011). Nitrogen deposition from human sources is estimated to contribute to a global net carbon sink in land ecosystems of 917 million metric tons (1,010 million tons) to 1,830 million metric tons (2,020 million tons) of CO_2 per year. These are model-based estimates, as comprehensive, data-based estimates at large spatial scales are hindered by a limited number of field experiments. This net land sink represents two components: an increase in vegetation growth as nitrogen limitation is alleviated by anthropogenic nitrogen deposition; and a contribution from the influence of increased reactive nitrogen availability on decomposition. While the former is generally enhanced with increased reactive nitrogen, the net effect on decomposition in soils is not clear. The net effect on total ecosystem carbon storage was an average of 37 metric tons (41 tons) of carbon stored per metric ton of nitrogen added in forests in the U.S. and Europe (Butterbach-Bahl 2011).

When all direct and indirect links between reactive nitrogen and climate in the U.S. are added up, a recent estimate suggests a modest cooling effect in the near term, but a progressive switch to net warming over a 100-year timescale (Pinder et al. 2012). That switch is due to a reduction in the cooling effects of NO_x emissions, a reduction in nitrogen-stimulated CO_2 sequestration in forests (for example, Thomas et al. 2010), and a rising importance of agricultural nitrous oxide emissions.

Changes in the phosphorus cycle have no direct radiative effects on climate, but phosphorus availability constrains plant and microbial activity in a wide variety of land- and water-based ecosystems (Elser et al. 2007; Vitousek et al. 2010). Changes in phosphorus availability due to human activity can therefore have indirect impacts on climate and the emissions of greenhouse gases in a variety of ways. For example, in land-based ecosystems, phosphorus availability can limit both CO_2 sequestration and decomposition (Cleveland and Townsend 2006; Elser et al. 2007) as well as the rate of nitrogen accumulation (Houlton et al. 2008).

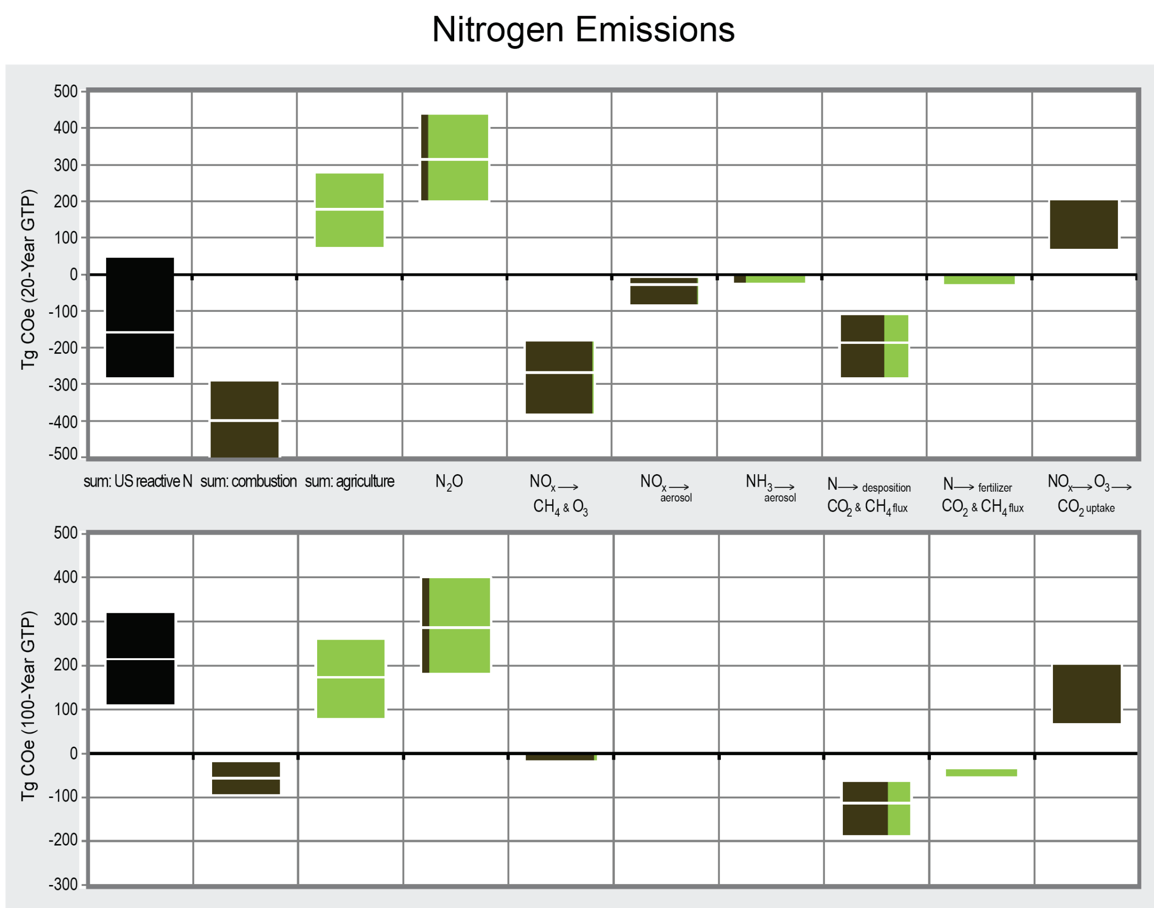

Figure 15.3: Nitrogen Emissions

Caption: Climate change will affect U.S. reactive nitrogen emissions, in Teragrams (Tg) CO_2 equivalents, on a 20-year (top) and 100-year (bottom) global temperature potential basis. The length of the bar denotes the range of uncertainty, and the white line denotes the best estimate. The relative contribution of combustion (brown) and agriculture (green) is denoted by the color shading. (Adapted from Pinder et al. 2012).

Other Effects: Sulfur Aerosols

In addition to the aerosol effects from nitrogen mentioned above, there are both direct and indirect effects on climate from other aerosol sources. Components of the sulfur cycle exert a cooling effect, through the formation of sulfate aerosols created from the oxidation of sulfur dioxide (SO_2) emissions (Forster et al. 2007). In the U.S., the dominant source of sulfur dioxide is coal combustion. Sulfur dioxide emissions rose until 1980 but, following a series of air-quality regulations and incentives focused on improving human health, as well as reductions in the delivered price of low-sulfur coal, emissions decreased by more than 50% between 1980 and the present day (EPA 2010b). That decrease has had a marked effect on U.S. climate forcing: between 1970 and 1990, sulfate aerosols caused cooling, primarily over the eastern U.S. Since 1990, further reductions in sulfur dioxide emissions have reduced the cooling effect of sulfate aerosols by half or more (Leibensperger et al. 2012). Continued declines in sulfate aerosol cooling are projected for the future, though at a much smaller rate than during the previous three decades because of the emissions reductions already realized (Leibensperger et al. 2012). Here, as with NO_x emissions, the environmental and socio-economic trade-offs are important to recognize: lower sulfur dioxide and NO_x emissions remove some climate cooling agents, but improve ecosystem health and save lives (Shindell et al. 2012; Suddick and Davidson 2012).

Three low-concentration industrial gases are particularly potent for trapping heat: nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and trifluoromethyl sulfur pentafluoride (SF_5CF_3). None currently makes a major contribution to climate forcing, but since their emissions are increasing and their effects last for millennia, continued monitoring is important.

Impacts and Options

Major biogeochemical cycles and climate change are inextricably linked, increasing the impacts of climate change on the one hand and providing a variety of ways to limit climate change on the other.

Climate change alters key aspects of biogeochemical cycling, creating the potential for feedbacks that alter both warming and cooling processes into the future. In addition, both climate and biogeochemistry interact strongly with environmental and ecological concerns, such as biodiversity loss, freshwater and marine eutrophication (unintended fertilization of aquatic ecosystems that leads to water quality problems), air pollution, human health, food security, and water resources. Many of the latter connections are addressed in other sections of this assessment, but we summarize some of them here because consideration of mitigation and adaptation options for changes in climate and biogeochemistry often requires this broader context.

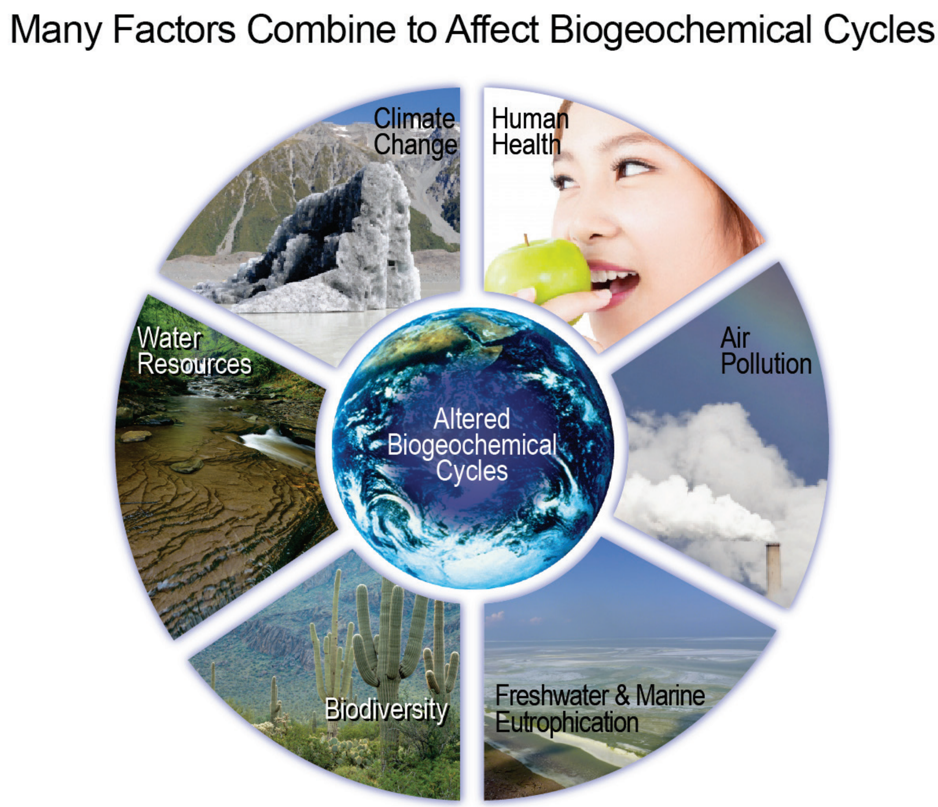

Figure 15.4: Many Factors Combine to Affect Biogeochemical Cycles

Caption: The interdependence of biogeochemical cycles, climate change, and other environmental stressors is shown in this illustration. Each section of this circle represents an important way that the planet's biological and chemical processes affect, and are affected by, other natural and human-caused changes. (Figure created by Nancy Grimm, Arizona State University)

Climate-biogeochemistry Feedbacks

Both rising temperatures and changes in water availability can alter climate-relevant biogeochemical processes. For example, as summarized above, nitrogen deposition drives temperate forest carbon storage both by increasing plant growth and by slowing organic-matter decomposition (Janssens et al. 2010; Knorr et al. 2005). Higher temperatures will counteract soil carbon storage by increasing decomposition rates and subsequent emission of CO_2 via microbial respiration. However, that same increase in decomposition accelerates the release of reactive nitrogen (and phosphorus) from organic matter, which in turn can fuel additional plant growth (Melillo et al. 2011). Temperature also has direct effects on net primary productivity. The combined effects on ecosystem carbon storage will depend on the extent to which nutrients constrain both net primary productivity and decomposition, on the extent of warming, and on whether any simultaneous changes in water availability occur (Dijkstra et al. 2012; Schimel et al. 2001; Wu et al. 2011).

Similarly, natural methane sources are sensitive to variations in climate; ice core records show a strong correlation between methane concentrations and warmer, wetter conditions (Loulergue et al. 2008). Large potential sources of methane in high-latitude regions from permafrost thawing are of particular concern.

Biogeochemistry, Climate, and Interactions with Other Factors

Societal options for addressing links between climate and biogeochemical cycles must often be informed by connections to a broader context of global environmental changes. For example, both climate change and nitrogen deposition can reduce biodiversity in water- and land-based ecosystems. The greatest combined risks are expected to occur where Critical Loads are exceeded (Baron 2006; Pardo et al. 2011). (A Critical Load is defined as the input of a pollutant below which no detrimental ecological effects occur over the long-term according to present knowledge.) (Pardo et al. 2011) Although biodiversity is often shown to decline when nitrogen deposition is high (Bobbink et al. 2010; Pardo et al. 2011), the compounding effects of multiple stressors are difficult to predict. Unfortunately, very few multi-factorial studies have been done to address this gap.

Human acceleration of the nitrogen and phosphorus cycles already causes widespread freshwater and marine eutrophication (Carpenter 2008; Howarth et al. 2011; Smith and Schindler 2009), a problem that is expected to worsen under a warming climate (Howarth et al. 2011; Jeppesen et al. 2010; Rabalais et al. 2009). Without efforts to reduce future climate change and to slow the acceleration of biogeochemical cycles, existing climate changes will combine with increasing nitrogen and phosphorus loading to freshwater and estuarine ecosystems and are projected to have substantial additive or synergistic effects on water quality, human health, inland and coastal fisheries, and greenhouse gas emissions (Baron et al. 2012; Howarth et al. 2011).

Similar concerns – and opportunities for the simultaneous reduction of multiple environmental problems (known as “co-benefits”) – exist in the realms of air pollution, human health, and food security. For example, methane, VOC, and NO_x emissions all contribute to the formation of tropospheric ozone, which in turn is both a greenhouse gas and has negative consequences for human health and crop productivity (Chameides et al. 1994; Davidson 2012; Jacob and Winner 2009). Rates of ozone formation are accelerated by higher temperatures, creating synergies between rising temperatures and continued human alteration of the nitrogen and carbon cycles (Peel et al. 2012). Rising temperatures work against some of the benefits of air pollution control (Jacob and Winner 2009). Some changes will trade gains in one arena for declines in others: For example, lowered NO_x, NH_x and SO_x emissions remove cooling agents from the atmosphere, but improve air quality (Shindell et al. 2012; Suddick and Davidson 2012). Recent analyses suggest that targeting reductions in compounds like methane that have both climate and air-pollution consequences can achieve significant improvements in not only the rate of climate change, but also in human health (Shindell et al. 2012). Similarly, reductions in excess nitrogen and phosphorus from agricultural and industrial activities can potentially reduce the rate and impacts of climate change, while simultaneously addressing concerns in biodiversity, water quality, food security, and human health. (Townsend and Porder 2012).

BOX 1. The U.S. Carbon Sink

Any natural or engineered process that temporarily or permanently removes and stores carbon dioxide (CO_2) from the atmosphere is considered a carbon "sink." Important CO_2 sinks at the global scale include absorption by plants as they photosynthesize, as well as CO_2 dissolution into the ocean. North America represents a large carbon sink in the global carbon budget; however, the spatial distribution and mechanisms controlling this sink are less certain (King et al. 2007). Understanding these processes is critical for predicting how land-based carbon sinks will change in the future, and potentially for managing the carbon sink as a mitigation strategy.

Both inventory and modeling techniques have been used to estimate land-based carbon sinks at a range of temporal and spatial scales. For inventory methods, carbon stocks are measured at a location at two points in time, and the amount of carbon stored or lost can be estimated over the intervening time period. This method is widely used to estimate the amount of carbon stored in forests in the United States over timescales of years to decades. Terrestrial biosphere models estimate carbon sinks by modeling a suite of processes that control carbon cycling dynamics, such as photosynthesis (CO_2 uptake by plants) and respiration (CO_2 release by plants, animals, and microorganisms in soil and water). Field-based data and/or remotely sensed data are used as inputs, and also to validate these models. Estimates of the land-based carbon sink can vary depending on the data inputs and how different processes are modeled (Hayes et al. 2012). Atmospheric inverse models use information about atmospheric CO_2 concentrations and atmospheric transport (like air currents) to estimate the terrestrial carbon sink (Ciais et al. 2010; Gurney et al. 2002). This approach can provide detailed information about carbon sinks over time. However, because atmospheric CO_2 is well-mixed and monitoring sites are widely dispersed, these models estimate fluxes over large areas and it is difficult to identify processes responsible for the sink from these data (Hayes et al. 2012). Recent estimates using atmospheric inverse models show that global land and ocean carbon sinks are stable or even increasing globally (Ballantyne et al. 2012).

The U.S. Environmental Protection Agency (U.S. EPA) conducts an annual inventory of U.S. greenhouse gas emissions and sinks as part of the nation's commitments under the Framework Convention on Climate Change. Estimates are based on inventory studies and models validated with field-based data (such as the CENTURY model) in accordance with the Intergovernmental Panel on Climate Change (IPCC) best practices (IPCC 2006). An additional comprehensive assessment, The First State of the Carbon Cycle Report, provides estimates for carbon sources and sinks in the U.S. and North America around 2003 (King et al. 2007). This assessment also utilized inventory and field-based terrestrial biosphere models, and incorporated additional land sinks not explicitly included in EPA assessments.

Data from these assessments suggest that the U.S. carbon sink has been variable over the last two decades, but still absorbs and stores a small fraction of CO_2 emissions. The forest sink comprises the largest fraction of the total land sink in the U.S., annually absorbing 7% to 24% (with a best estimate of 13%) of fossil fuel CO_2 emissions during the last two decades. Because the U.S. Forest Service has conducted detailed forest carbon inventory studies, the uncertainty surrounding the estimate for the forest sink is lower than for most other components (Table 2; Pacala et al. 2007). The role of lakes, reservoirs, and rivers in the carbon budget, in particular, has been difficult to quantify and is rarely included in national budgets (Cole et al. 2007). The

IPCC guidelines for estimating greenhouse gas sources or sinks from lakes, reservoirs, or rivers are included in the "wetlands" category, but only for lands converted to wetlands. These ecosystems are not included in the Environmental Protection Agency's estimates of the total land sink. Rivers and reservoirs were estimated to be a sink in the State of the Carbon Cycle analysis (Pacala et al. 2007; Figure 2), but recent studies suggest that inland waters may actually be an important source of CO_2 to the atmosphere (Butman and Raymond 2011).

Carbon (C) sinks and uncertainty estimated by Pacala et al. (2007) for the first State of the Carbon Cycle Report.

Land Area	**C sink (Mt C/y) (95% CI)**	**Method**
Forest	-256 (+/- 50%)	inventory, modeled
Wood products	-57 (+/- 50%)	inventory
Woody encroachment	-120 (+/- >100%	inventory
Agricultural soils	-8 (+/- 50%	modeled
Wetlands	-23 (+/- >100%)	inventory
Rivers and reservoirs	-25 (+/- 100%)	Inventory
Net Land Sink	**-489** (+/- 50%)	inventory

Table 15.1: Land-based Carbon Sinks

Caption: Forests take up the highest percentage of carbon of all land-based carbon sinks. Due to a number of factors, there are high degrees of uncertainty in carbon sink estimates.

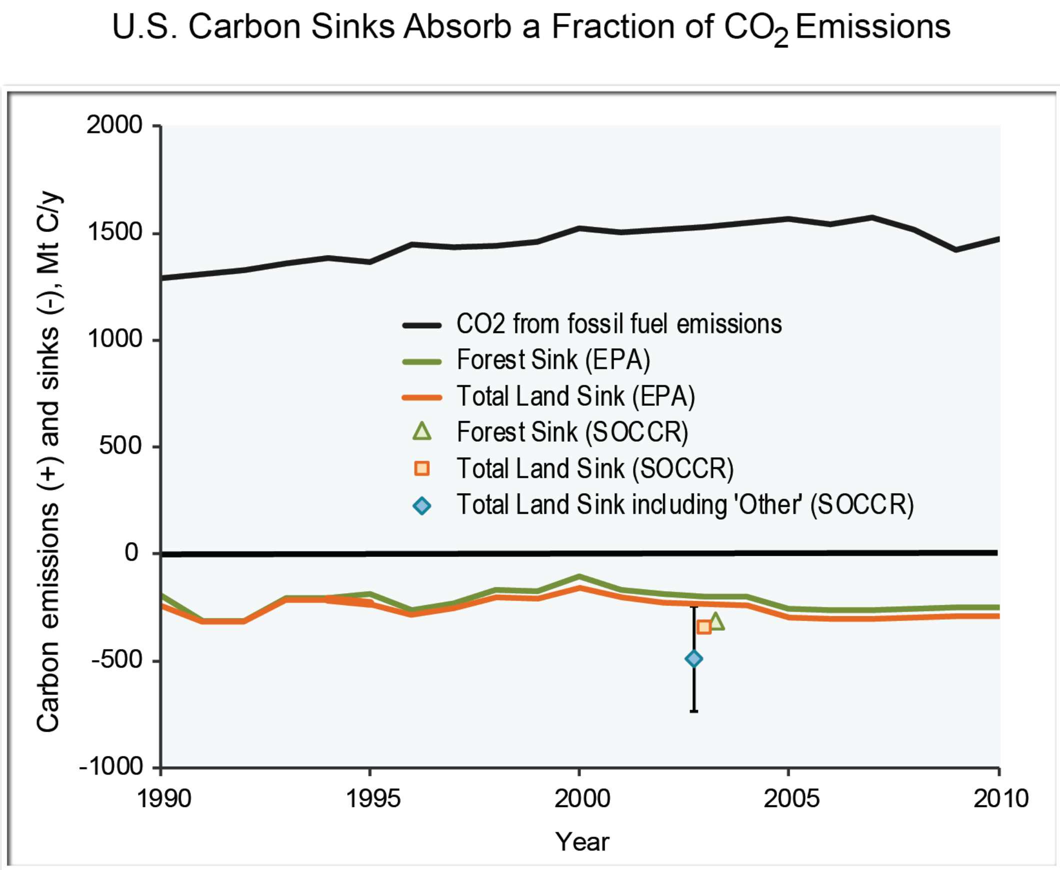

Figure 15.5: U.S. Carbon Sinks Absorb a Fraction of CO_2 Emissions

Caption: Chart shows growth in fossil-fuel CO_2 emissions (black line) and forest and total land carbon sinks in the U.S. from 1990–2010 (green and orange lines; EPA 2012) and for 2003 from the first State of the Carbon Cycle Report (SOCCR) (2007). Carbon emissions are significantly higher than the total land sink's capacity to absorb and store them.

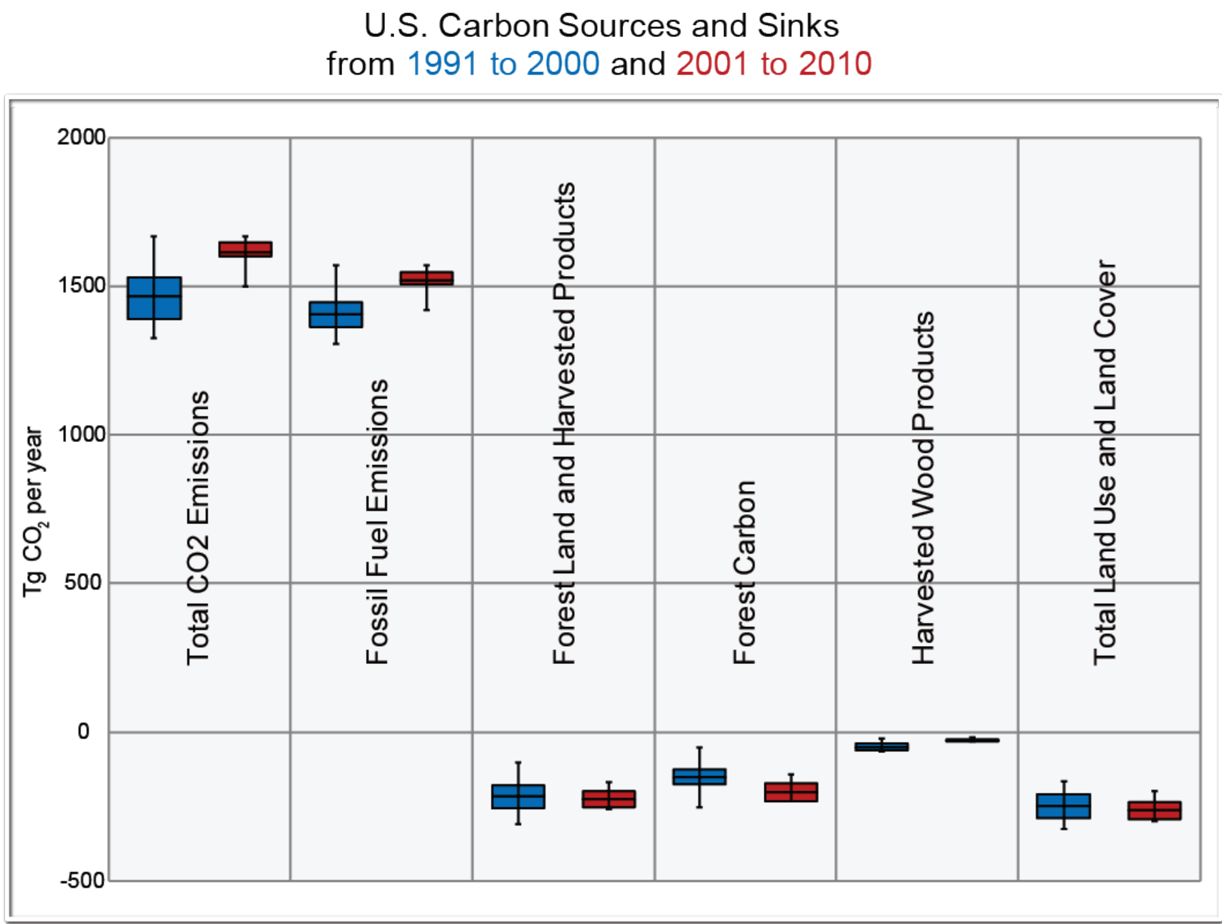

Figure 15.6: U.S. Carbon Sources and Sinks from 1991 to 2000 (blue) and 2001 to 2010 (red)

Caption: Changes in CO_2 emissions and land-based sinks in two recent decades, showing among-year variation (lines: minimum and maximum estimates among years; boxes: 25^{th} and 75^{th} quartiles; horizontal line: median). Total CO_2 emissions, as well as total CO_2 emissions from fossil fuels, have risen; land-based carbon sinks have increased slightly, but at a much slower pace. Data from (EPA 2012) and (CCSP 2007).

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Traceable Accounts

Chapter 15: Biogeochemical Cycles

Key Message Process: The key messages and supporting text summarize extensive evidence documented in two technical input reports submitted to the NCA: 1) a foundational report co-edited by W. Post and R. Venterea (2012): Biogeochemical cycles and biogenic greenhouse gases from North American terrestrial ecosystems: A Technical Input Report for the National Climate Assessment. Washington, DC. and supported by the Departments of Energy and Agriculture), and 2) an external report, Suddick, E. C. and E. A. Davidson, editors (2012): The role of nitrogen in climate change and the impacts of nitrogen-climate interactions on terrestrial and aquatic ecosystems, agriculture, and human health in the United States: a technical report submitted to the US National Climate Assessment. North American Nitrogen Center of the International Nitrogen Initiative (NANC-INI), Woods Hole Research Center, Falmouth, MA), supported by the International Nitrogen Initiative, a National Science Foundation grant, and the U.S. Geological Survey. Author meetings and workshops were held regularly for the Post and Venterea (2012) report, including a workshop at the 2011 Soil Science Society of America meeting. A workshop held in July 2011 at the USGS John Wesley Powell Center for Analysis and Synthesis in Fort Collins, CO focused on climate-nitrogen actions and was summarized in the Suddick and Davidson (2012) report. Both reports are in review or in press as a series of papers in special issues of the journals *Frontier of Ecology and the Environment* and *Biogeochemistry*, respectively. An additional 15 technical input reports on various topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The "Biogeochemistry" author team conducted its deliberations by teleconference from April to June, 2012, with three major meetings resulting in an outline and a set of key messages. All authors were in attendance for these teleconferences. The team came to expert consensus on all of the key messages based on their reading of the technical inputs, other published literature, and professional judgment. Several original key messages were later combined into a broader set of statements while retaining most of the original content of the chapter. Major revisions to the key messages, chapter, and these traceable accounts were approved by authors; further minor revisions were consistent with the messages intended by the authors.

Key message #1/3	**Human activities have increased CO2 by more than 30% over background levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends are seen for phosphorus, sulfur, and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
Description of evidence base	The author team evaluated Technical Input reports (17) on biogeochemical cycles, including the two primary sources (Shindell et al. 2012; Suddick and Davidson 2012).In particular, the Suddick and Davidson report focused on changes in the nitrogen cycle and was comprehensive. Original literature was consulted for changes in other biogeochemical cycles. The Post and Venterea (2012) report updated several aspects of our understanding of the carbon balance in the U.S. Publications have shown that human activities have altered biogeochemical cycles. A seminal paper comparing increases in the global fluxes of C, N, S, and P was published in 2000 and has yet to be updated specifically (Falkowski et al. 2000). However, changes observed in the nitrogen cycle (Baron et al. 2012; Galloway et al. 2003; Galloway et al. 2008; Vitousek et al. 1997) show anthropogenic sources to be far greater than natural ones (EPA 2011b; Houlton et al. 2012; Vitousek et al. 2010). For phosphorus, the effect of added phosphorus on plants and microbes is well understood (Elser et al. 2007; MacDonald et al. 2011; Smil 2000; Vitousek et al. 2010). Extensive research that shows increases in CO_2 to be the strongest anthropogenic climate-change force, mainly because its concentration is so much greater than other greenhouse gases (Falkowski et al. 2000; IPCC 2007; King et al. 2012).

New information and remaining uncertainties	Because the sources of C, N, S and P are from well-documented processes, such as fossil-fuel burning and fertilizer production and application, the uncertainties are small. Some new work has been synthesized for the assessment of the global and national CO_2 emissions (King et al. 2012), and categorizing the major sources and sinks (Post et al. 2012; Suddick and Davidson 2012). Annual updates of CO_2 emissions and sink inventories are done by the EPA (e.g., EPA 2012). Advances in the knowledge of the nitrogen cycle have quantified that human-caused reactive nitrogen inputs are now five times greater than natural inputs (EPA 2011a; Houlton et al. 2012; Suddick and Davidson 2012).
Assessment of confidence based on evidence	**Very high** confidence. Evidence for human inputs of C, N, S and P come from academic, government and industry sources. The data show substantial agreement. The likelihood of continued dominance of CO_2 over other greenhouse gases as a driver of global climate change is also judged to be **high**, because its concentration is an order of magnitude higher and its rate of change is well known.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 15: Biogeochemical Cycles

Key Message Process: See key message #1.

Key message #2/3	**Net uptake of CO2 by ecosystems of North America captures CO_2 mass equivalent to only a fraction of fossil-fuel CO2 emissions, with forests accounting for most of the uptake (7-24%, with a best estimate of 13%). The cooling effect of this carbon "sink" partially offsets warming from emissions of other greenhouse gases.**
Description of evidence base	The author team evaluated Technical Input reports (17) on biogeochemical cycles, including the two primary sources (Post et al. 2012; Suddick and Davidson 2012). The author team also contributed to a summary box on the carbon cycle (link), which is the source for the first part of this key message. The summary box relies on multiple sources of data that are described therein. Numerous studies of the North American and U.S. carbon sink have been published in reports and the scientific literature. The figure used in this chapter is from data in King et al. (2012). Estimates of the percentage of fossil-fuel CO_2 emissions that are captured by forest, cropland, and other lands vary from a low of 10% to a high of about 35%, when the carbon sink is estimated from carbon inventories (EPA 2011b; Hayes et al. 2012; King et al. 2012). Woodbury et al. (2007) show that the forest sink has persisted in the U.S. as forests that were previously cut have regrown. Further studies show that carbon uptake can be increased to some extent by a fertilizations effect with reactive nitrogen (Butterbach-Bahl 2011; Melillo et al. 2011) and phosphorus (Cleveland and Townsend 2006; Elser et al. 2007; Vitousek et al. 2010), both nutrients that can limit the rate of photosynthesis. The carbon sink due to nitrogen fertilization is projected to lessen in the future as controls on nitrogen deposition come into play (Pinder et al. 2012; Thomas et al. 2010). While carbon uptake by ecosystems has a net cooling effect, trace gases emitted by ecosystems have a warming effect that can offset the cooling effect of the carbon sink (Forster et al. 2007). The most important of these gases are methane and nitrous oxide (N_2O), the concentrations of which are projected to rise (Davidson 2012; Forster et al. 2007; Montzka et al. 2011; Prinn 2004; Robertson and Vitousek 2009; Robertson et al. 2012; Tian et al. 2012).
New information and remaining uncertainties	The carbon sink estimates have very wide margins of error, and the percentage sink depends on which years are used for emissions and whether inventories, ecosystem process models, atmospheric inverse models, or some combination of these techniques are used to estimate the sink size (see "U.S. Carbon Sink"box). The inventories are continually updated (for example, EPA 2012), but there is a lack of congruence on which of the three techniques is most reliable. A recent paper that uses atmospheric inverse modeling suggests that the global land and ocean carbon sinks are stable or increasing (Ballantyne et al. 2012). While known to be significant, continental-scale fluxes and sources of the greenhouse gases N_2O and CH_4 are based on limited data and are potentially subject to revision. The syntheses in Pinder et al. (2012) and Tian et al. (2012) evaluate the dynamics of these two important gases and project future changes. Uncertainties remain high.
Assessment of confidence based on evidence	We have **very high** confidence that the value of the carbon sink lies within the range given. There is wide acceptance that forests and soils store carbon in North America, and that they will continue to do so into the near future. The exact value of the sink strength is very poorly constrained, however, and knowledge of the

	likely future sink is low. As forests age, their capacity to store carbon in living biomass will necessarily decrease (Woodbury et al. 2007), but if other, unknown sinks are dominant, ecosystems may continue to be a carbon sink. We have **high** confidence that the combination of carbon sink and potential offsets from other trace gases will ultimately result in a net warming effect. This is based primarily on the analysis of Pinder et al. (2012). However, the exact amount of warming or cooling produced by various gases is not yet well constrained, because of the interactions of multiple factors.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/3	**Major biogeochemical cycles and climate change are inextricably linked, increasing the impacts of climate change on the one hand and providing a variety of ways to limit climate change on the other.**
Description of evidence base	The author team evaluated Technical Input reports (17) on biogeochemical cycles, including the two primary sources (Post et al. 2012; Suddick and Davidson 2012). The climate–biogeochemical cycle link has been demonstrated through numerous studies on the effects of reactive nitrogen and phosphorus on forest carbon uptake, storage, and decomposition (Janssens et al. 2010; Knorr et al. 2005; Melillo et al. 2011), temperature effects on ecosystem productivity (Dijkstra et al. 2012; Schimel et al. 2001; Wu et al. 2011), and natural methane emission sensitivity to climate variation (Loulergue et al. 2008). Where the nitrogen and phosphorus cycles are concerned, a number of publications have reported effects of excess loading on ecosystem processes (Carpenter 2008; Howarth et al. 2011; Smith and Schindler 2009) and have projected these effects to worsen (Howarth et al. 2011; Jeppesen et al. 2010; Rabalais et al. 2009). Additionally, studies have reported the potential for the future climate change and increasing nitrogen and phosphorus loadings to have an additive effect and the need for remediation (Baron et al. 2012; Howarth et al. 2011). The literature suggests that co-benefits are possible from addressing these environmental concerns of nutrient loading and climate change (Jacob and Winner 2009; Peel et al. 2012; Shindell et al. 2012; Suddick and Davidson 2012; Townsend and Porder 2012).
New information and remaining uncertainties	Scientists are still investigating the impact of nitrogen deposition on carbon uptake, and of sulfur and nitrogen aerosols on radiative forcing. Recent work has shown that more than just climate change aspects can benefit from addressing multiple environmental concerns (air/water quality, biodiversity, food security, human health, etc.)
Assessment of confidence based on evidence	**High**. There is agreement that nitrogen deposition can stimulate carbon uptake in forests. The major questions concern the magnitude and the length of time that forests will provide this service.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Introduction to the Regions

Landscapes, ecosystems, communities, and economies vary dramatically across our country's disparate regional geographies, but also share many common attributes. Each region is affected by changes in the global and national economy; each adds to our complex and multifaceted culture; each is connected to the same integrated infrastructure – such as transportation, communications, and energy systems – and they are all affected by the changing climate.

In some regions, the evidence of climate change impacts is more obvious than others. The most dramatic evidence is in Alaska, where average temperatures have increased more than twice as fast as the rest of the country. Of all the climate related changes in the U.S., the rapid decline of Arctic ice cover in the last decade may be the most striking of all. But the rest of the country is also experiencing visible shifts. In the Southwest, a combination of increased temperatures and reductions in annual precipitation are already affecting forests and diminishing water supplies. Meanwhile, the region's population continues to grow at double-digit rates, increasing the stress on water supplies. In other regions, the evidence of climate change is most obvious in ecosystem changes, such as species moving northwards, increases in invasive species and insect outbreaks, and changes in the length of the growing season. For other places, impacts to the urban environment are closely linked to the changing climate, with increased flooding, higher incidence of heat waves, and diminishing air quality. Finally, all regions with ocean coastlines are concerned about increasing sea levels threatening coastal areas and infrastructure.

These regional differences provide opportunities as well. A changing climate brings alterations in historical agricultural practices that can be beneficial if properly anticipated. Warmer winters mean reductions in heating costs for those in the northern portions of the country. Well-designed adaptation and mitigation actions, optimized appropriately for regional differences, can significantly enhance the nation's resilience in the face of multiple challenges that include many factors other than climate change.

The regions defined in this report intentionally follow state lines, but it's obvious that landscape features such as forests or mountain ranges do not follow these artificial boundaries, and the range of distinct landscapes within each region required difficult choices of emphasis for chapter authors. The chapters that follow provide a summary of changes that are observed and anticipated in each of the eight regions of the U.S., as well as on Oceans and Coasts.

16. Northeast

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Key Messages

1. **Heat waves, coastal flooding due to sea level rise, and river flooding due to more extreme precipitation events will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially populations that are already most disadvantaged.**
2. **Infrastructure will be increasingly compromised by climate-related hazards including sea level rise and coastal flooding, and intense precipitation events.**
3. **Agriculture and ecosystems will be increasingly stressed by climate-related hazards, including higher temperatures, sea level rise and coastal flooding, and more extreme precipitation events. A longer growing season may allow farmers to explore new crop options, but this and other adaptations will not be cost or risk-free, and inequities exist in the capacity for adaptation.**
4. **While a majority of states and several municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.**

Introduction

Sixty-four million people are concentrated in the Northeast. The high-density urban coastal corridor from Washington, D.C. north to Boston is one of the most built-up environments in the world, and it contains a huge, long-standing network of supporting infrastructure. The region is home to the world's leading financial center and many of the nation's defining cultural and historical landmarks – they annually draw millions of visitors from all over the world.

The Northeast also includes large expanses of sparsely populated but ecologically and agriculturally important areas. Much of the Northeast landscape is dominated by forest, but the region also has grasslands, coastal zones, beaches and dunes, and wetlands, and it is known for its rich marine and freshwater fisheries. These natural areas are essential to recreation and tourism sectors and support jobs through the sale of timber, maple syrup, and fish. They also contribute important ecosystem services to broader populations – protecting water supplies, buffering shorelines, and sequestering carbon in soils and vegetation. The twelve Northeastern states have more than 180,000 farms, with $17 billion in annual sales (USDA 2007). The region's ecosystems and agricultural systems are tightly interwoven, and both are vulnerable to a changing climate.

Although urban and rural regions in the Northeast are profoundly different, they both include populations that are highly vulnerable to climate hazards and other stresses. Both depend on aging infrastructure that has already been stressed by climate hazards including heat waves, as well as coastal and riverine flooding due to a combination of sea level rise, storm surge, and extreme precipitation events.

The Northeast is characterized by a highly diverse climate (Horton et al. 2012). Average temperatures in the Northeast generally decrease to the north and with distance from the coast and elevation. Average annual precipitation varies by about 20 inches throughout the Northeast with the highest amounts observed in coastal and select mountainous regions. During winter, frequent storms bring bitter cold and frozen precipitation, especially to the north. Summers are warm and humid, especially to the south. The Northeast is often affected by extreme events such as ice storms, floods, droughts, heat waves, hurricanes, and nor'easters. However variability is large in both space and time. For example, parts of Southern New England that experienced heavy snows in the winter of 2010-2011, experienced almost no snow during the winter of 2011-2012 (although a costly Halloween storm knocked out power for up to 10 days for thousands of households).

Observed Climate Change

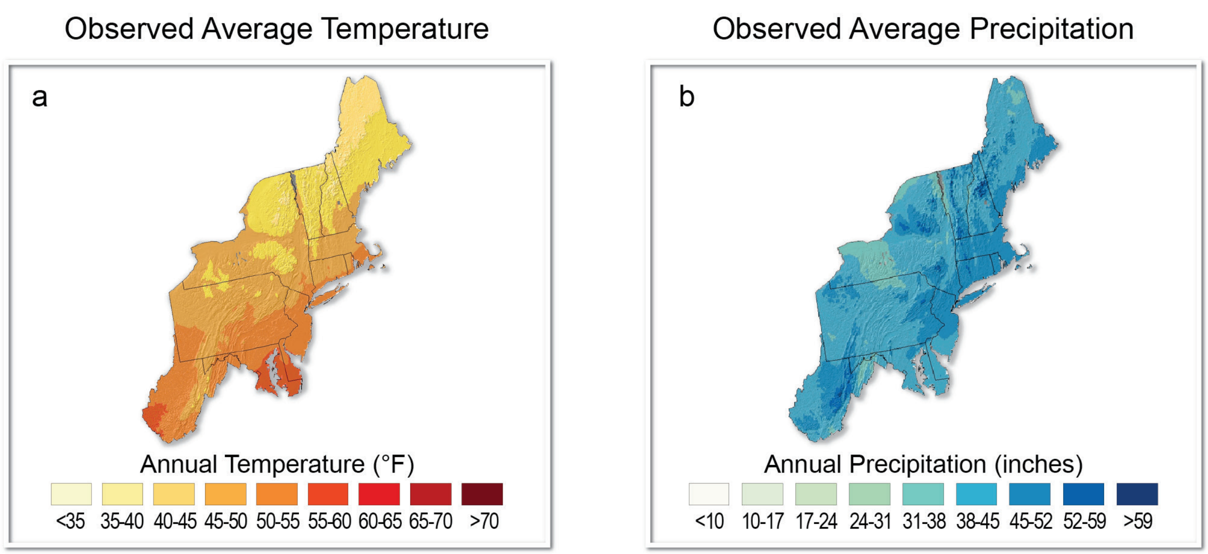

Figure 16.1: Observed Average Temperature and Precipitation

Caption: (a) Annual average temperature (°F) for 1981-2010. Because this average includes data from more stations at lower elevations than at higher elevations, the map does not fully represent the full range of temperature, particularly at higher elevations. (b) Annual average precipitation (inches) for 1981-2010. (Kunkel et al. 2012)

Between 1895 and 2011, temperatures in the Northeast increased by almost 2˚F (0.16˚F per decade), and precipitation increased by approximately 5 inches, or more than 10% (0.4 inches per decade) (Kunkel et al. 2012). Coastal flooding has increased due to sea level rise of approximately 1 foot since 1900. This rate of sea level rise exceeds the global average of approximately 8 inches (see Ch. 2: Our Changing Climate, key message 9), due primarily to land subsidence (Church et al. 2010), although recent research suggests that changes in ocean circulation in the North Atlantic – specifically, a weakening of the Gulf Stream – may also play a role (Sallenger et al. 2012).

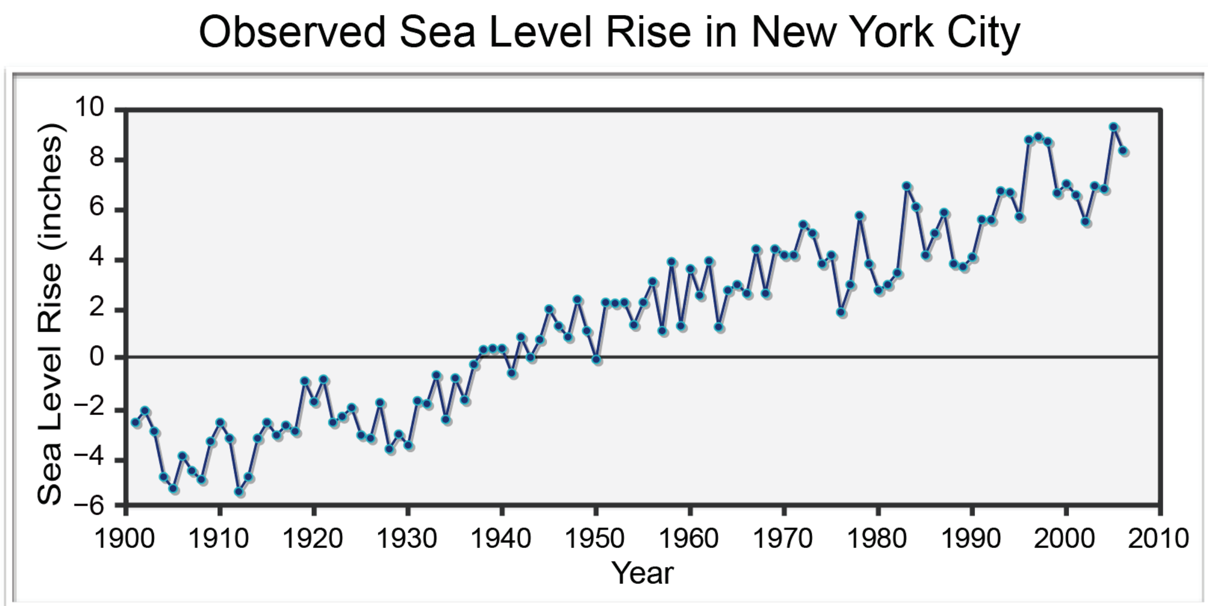

Figure 16.2: Observed Sea Level Rise in New York City

Caption: Observed sea level at the Battery, New York City has significantly exceeded the global average of 8 inches over the past century, increasing the risk of impacts to critical urban infrastructure in low-lying areas. Over 100 years, sea level increased 1.2 feet (Source: New York City Panel on Climate Change 2010).)

The Northeast has experienced a greater increase in extreme precipitation over the past few decades than any other region in the U.S.; between 1958 and 2010, the Northeast saw a 74% percent increase in the amount of precipitation falling in very heavy events.

Projected Climate Change

Warming in the Northeast will be highly dependent on global emissions of heat-trapping gases. If emissions continue to increase (as in the A2 scenario), warming of 4.5ºF to 10ºF is projected by the 2080s; if global emissions were reduced substantially (as in the B1 scenario), projected warming ranges from about 3ºF to 6ºF by the 2080s (Kunkel et al. 2012).

Under both emissions scenarios, the frequency, intensity, and duration of heat waves is expected to increase, with larger increases under higher emissions. Regional climate model simulations suggest that the southern part of the region, including large parts of West Virginia, Maryland, and Delaware could experience more than a doubling of days per year over 95ºF by the 2050s .

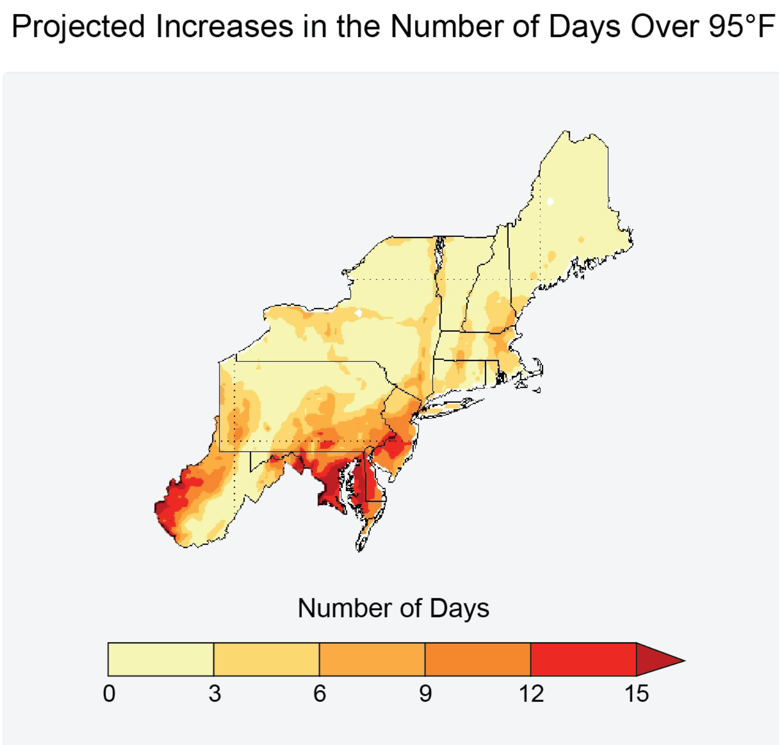

Figure 16.3: Projected Increases in the Number of Days over 95°F.

Caption: Projected average increases in the number of days with a maximum temperature greater than 95°F between 2041-2070, compared to 1971-2000 assuming continued increases in global emissions (A2 scenario). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Multi-model Mean.)

Much of the southern portion of the region, including the majority of Maryland, and Delaware, and southwest West Virginia and New Jersey, are projected to experience more than 15 additional days per year above 95°F, which will impact the regions vulnerable populations, infrastructure, and agriculture and ecosystems.

The frequency, intensity, and duration of cold air outbreaks is expected to decrease as the century progresses, although some research suggests that this trend may be slowed by compensating factors such as indirect effects on the region of melting Arctic sea ice (for example, Liu et al. 2012).

Projections of precipitation changes are less certain than projections for temperature increases (Kunkel et al. 2012). Winter precipitation is projected to increase, especially but not exclusively in the northern part of the region (Karl et al. 2009; Kunkel et al. 2012; Ch. 2: Our Changing Climate; Key Messages 5 & 6). A range of model projections for the end of this century under a high emissions scenario (A2), averaged over the region, suggests 1% to 29% increases in winter precipitation. Projections in other seasons, and for the entire year, range from moderate decreases to large increases (Kunkel et al. 2012; Ch. 2: Our Changing Climate; Key Message 5). The frequency of heavy downpours is projected to continue to increase as the century progresses (Ch. 2: Our Changing Climate). Seasonal drought risk is also projected to increase in summer and fall as higher temperatures lead to greater evaporation and earlier winter and spring snowmelt (Horton and Rosenzweig 2010).

Global sea levels are projected to rise between 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 9) depending in large part on the extent to which the Greenland and the West Antarctic Ice Sheets experience significant melting. Sea level rise in the Northeast is expected to exceed the global average by up to roughly 4 inches per century due to local land subsidence, with the possibility of even greater regional sea level rise if the Gulf Stream weakens as some models suggest (Yin et al. 2009; Yin et al. 2011).

Even given the low end of sea level rise scenarios, and without assuming any changes in storms, the chance of what is now a 1-in-10-year coastal flood event in the Northeast could triple by 2100, occurring roughly once every 3 years, simply in response to higher sea levels (Horton et al. 2011; Tebaldi et al. 2012).

Hurricanes such as Irene and Sandy provided a “teachable moment” by demonstrating the region’s vulnerability to extreme weather events and the efficacy of existing and evolving adaptation/response plans.

Box: Hurricane Vulnerability

Two recent events contrast existing vulnerability to extreme events: Hurricane Irene, which produced a broad swath of very heavy rain (greater than 5 inches in total and sometimes 2 to 3 inches per hour in some locations) from southern Maryland to northern Vermont from August 27 to 29, 2011; and Hurricane Sandy which caused massive coastal damage from storm surge and flooding.

The rainfall associated with Irene exceeded the estimated 1-in-500-year storm at Delanson, NY and Waterbury, VT. These heavy rains were part of a broader pattern of wet weather preceding the storm that exacerbated the flooding associated with Irene; rainfall totals for August and September exceeded 25 inches across much of the Northeast.

Flooding and Hurricane Irene

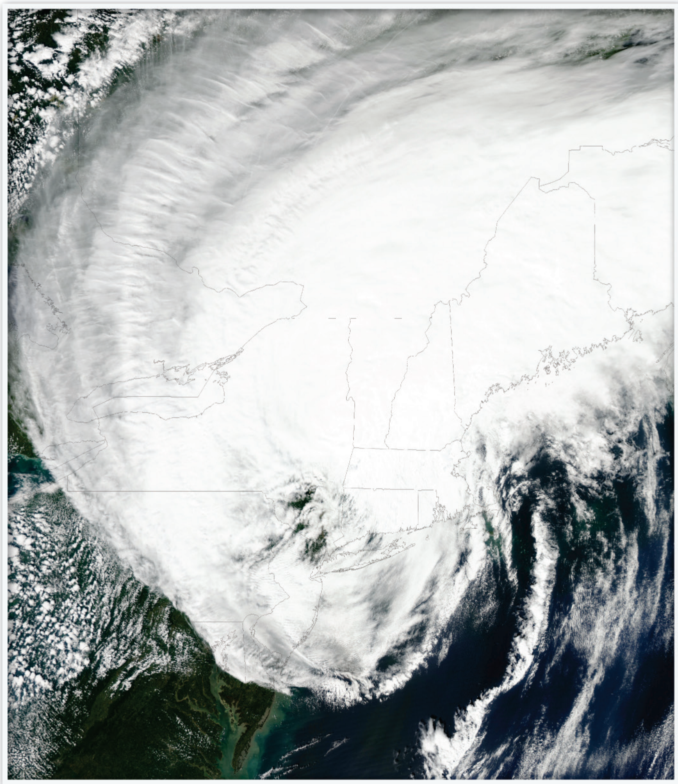

Figure 16.4: Flooding and Hurricane Irene

Caption: Hurricane Irene brought a broad swath of very heavy rain (greater than five inches in total and 2 to 3 inches per hour in some locations), producing severe flooding from southern Maryland to northern Vermont from August 27 to 29, 2011. Satellite image shows Irene over the Northeast on August 28, 2012. The storm also took approximately 50 lives, and the economic cost was estimated to be approximately $15 billion (Avila and Cangliosi 2011; Avila and Stewart 2012). (Source: NASA Satellite Image)

In anticipation of Irene, the New York City mass transit system was shut down, and 2.3 million coastal residents in Delaware, New Jersey, and New York faced mandatory evacuations. But it was the inland impacts, especially in upstate New York and in central and southern Vermont, that were most severe. Flash flooding washed out roads and bridges, undermined railroads, brought down trees and power lines, flooded homes and businesses, and damaged floodplain forests. In Vermont, over 500 miles of state-owned roadways and approximately 200 bridges were damaged, with estimated rebuilding costs of $175-250 million. Hazardous wastes were released in a number of areas, and 17 municipal wastewater treatment plants were breached by the floodwaters. Agricultural losses included damage to barn structures and flooded fields of crops. Infrastructure impacts from river flooding led to many towns and villages being isolated for many days (Horton et al. 2012).

Sandy took approximately 130 lives in the U.S. alone, and monetary impacts on coastal areas, especially in New Jersey, New York, Connecticut, and Rhode Island may be approximately $60 to $80 billion (NY Times 11/27; NY Times 12/5). Floodwaters inundated subway tunnels in New York City, up to 8 million people lost electricity, and, according to preliminary estimates, between 20,000 and 100,000 families may have lost their homes (NY Times 11/27). Many of these vulnerabilities to coastal flooding and sea level rise (Ch. 2: Our Changing Climate, Key Message 9) and intensifying storms (Ch. 2: Our Changing Climate, Key Message 8) – including the projected frequency of flooding of tunnels and airports – were documented as early as 2001 in a report developed in support of the 2000 National Climate Assessment (Rosenzweig and Solecki 2001). The observed vulnerability was not a surprise in New York, given its 600 miles of coastline and over half a million people living within the current flood plain.

Through follow-on activities in New York City and New York State that included regional decision makers such as the Port Authority, Metropolitan Transportation Authority, and utility companies, a process, approach, and tools for climate change adaptation in the New York City (City of New York 2011; Rosenzweig and Solecki 2010) and New York State (Rosenzweig et al. 2011b) were formulated. This process, and resulting adaptation efforts including elevating infrastructure and restoring green spaces, helped reduce damage and save lives (also see discussion of Hurricane Sandy in Ch. 11: Urban Vulnerability and Infrastructure). As rebuilding advances, serious consideration of current and projected risks from such events by a full set of stakeholders and participants could dramatically improve resilience against future extreme events.

Coastal Flooding Along New Jersey's Shore

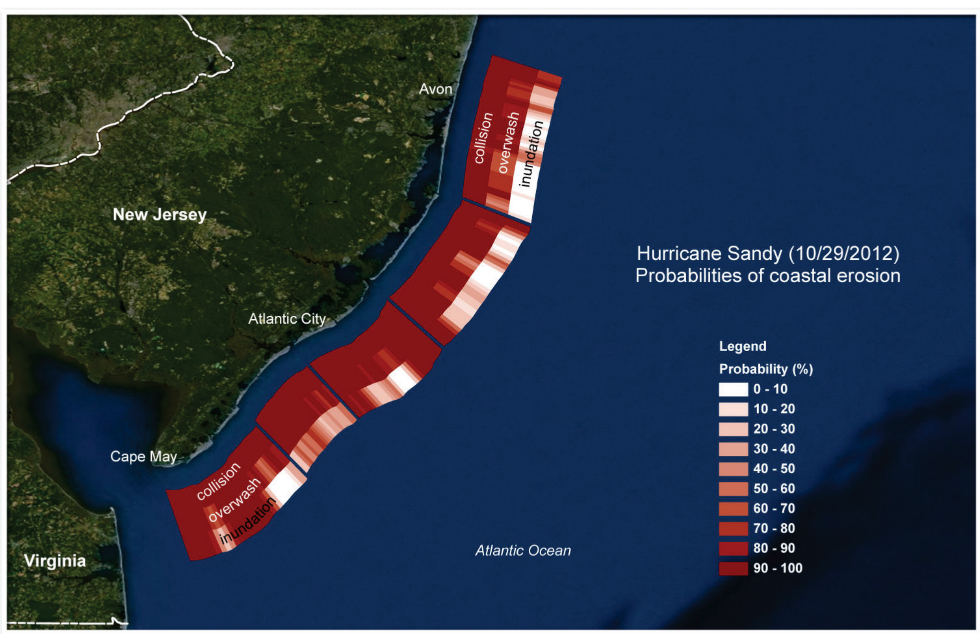

Figure 16.5: Coastal Flooding Along New Jersey's Shore

Caption: Predictions of coastal erosion prior to Sandy's arrival provided advance warning of potential vulnerability to the regions residents and decision-makers. The map shows three bands: collision of waves with beaches causing erosion on the front of the beach; overwash that occurs when water reaches over the highest point and erodes from the rear, which carries sand inland; and inundation, when the shore is severely eroded and new channels can form that leads to permanent flooding. The probabilities are based on the storm striking at high tide. For New Jersey, the model estimated that 21% of the shoreline had more than a 90% chance of experiencing inundation. These projections were realized, and made the New Jersey coastline even more vulnerable to the Nor'easter that followed Hurricane Sandy by only 10 days. (Source: USGS 2012)

-- end box --

Climate Risks to People

Heat waves, coastal flooding due to sea level rise, and river flooding due to more extreme precipitation events will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially populations that are already most disadvantaged.

Urban residents have unique and multifaceted vulnerabilities to heat extremes. Temperatures tend to be higher in urban areas; during extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher (Gaffin et al. 2008) than surrounding regions, leading to increased heat-related death among those less able to recover from the heat of the day (Semenza et al. 1996). Since the hottest days in the Northeast are often associated with high concentrations of ground level ozone and other pollutants (Patz 2000), the combination of heat stress and poor air quality can pose a major health risk to vulnerable groups: young children, the elderly, and those with pre-existing health conditions including asthma (Solecki et al. 2011). Vulnerability is further increased as key infrastructure, including electricity for life-saving cooling, is more likely to fail precisely when it is most needed – when demand exceeds available supply. Significant investments may be required to insure that power generation keeps up with increases in demand associated with rising temperatures, not even accounting for extreme events (Amato et al. 2005; Ruth and Lin 2006). Finally, vulnerability to heat waves is not evenly distributed throughout urban areas; outdoor versus indoor air temperatures, air quality, baseline health, and access to air conditioning are all dependent on socioeconomic factors (Solecki et al. 2011).

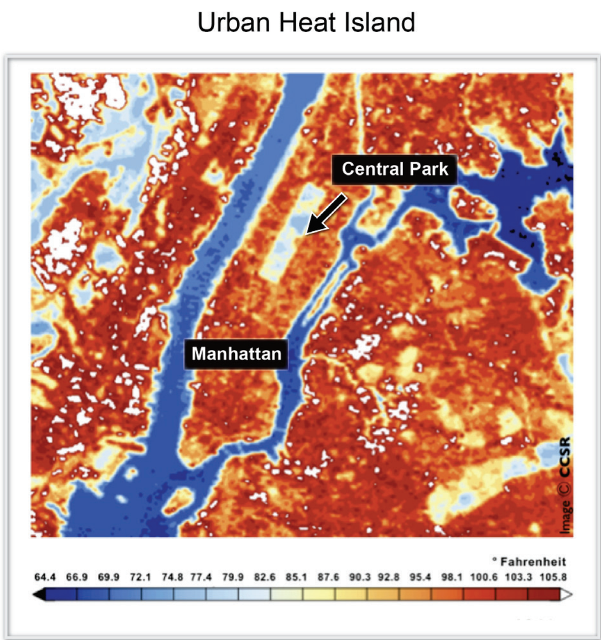

Figure 16.6: Urban Heat Island

Captions: Surface temperatures in New York City on a summer's day show the "urban heat island", with temperatures in populous urban areas being approximately 10°F higher than the forested parts of Central Park. Dark blue reflects the colder waters of the Hudson and East Rivers. (Source, Data are from NASA Landsat 7, Band 6. Source: Center for Climate Systems Research, Columbia University.)

Increased health-related impacts and costs, such as premature death and hospitalization due to even modest increases in heat, are predicted (Anderson and Bell 2012; EPA 2006; Huang et al. 2011; Knowlton et al. 2007) in the Northeast's urban centers. Increased ground-level ozone due to warming is projected to increase ozone-related asthma emergency department visits by 7.3% in 2020 in the New York metropolitan area (Sheffield et al. 2011b).

Heat wave research has tended to focus on urban areas, but vulnerability to heat may also become a major issue in rural areas and small towns because air conditioning is currently not prevalent in parts of the rural Northeast where heat waves have historically been rare. For western New York and western Massachusetts, it is projected that by the 2050s, an additional 5 or more days per year over 95°F may occur by the 2050s – regions where days over 95°F are currently relatively rare (Kunkel et al. 2012). It should be noted that winter heating needs, a significant expense for many Northeastern residents, are likely to decrease as the century progresses (Hammer et al. 2011).

Historical settlement patterns and on-going investment in coastal areas and along major rivers combine to increase the vulnerabilities of people in the Northeast to sea level rise and coastal storms. Of the Northeast's population of 64 million (U.S. Census Bureau 2010), approximately 1.6 million people live within the FEMA 100-year coastal flood zone, with the majority – 63% of those at risk – residing in New York and New Jersey (Crowell et al. 2010). As sea level rise increases in the future, populations in the current 1-in-100-year coastal flood zone will experience more frequent flooding, and populations that have historically fallen outside the 1-in-100-year flood zone will find themselves in that zone. Populations living in coastal flood zones are vulnerable to direct loss of life and injury associated with tropical storms and Nor'easters. Flood damage to personal property, businesses, and public infrastructure can also result (see next section).

This risk is not limited to the 1-in-100-year flood zone; in the Mid-Atlantic part of the region alone, estimates suggest that between 450,000 and 2.3 million people are at risk from a three foot sea level rise (CCSP 2009), which is in the range of projections for this century.

Throughout the Northeast, populations are also concentrated along rivers and their flood plains. In mountainous regions, including much of West Virginia and large parts of Pennsylvania, New York, Vermont, and New Hampshire, more intense precipitation events (Kunkel et al. 2012) will mean greater flood risk to populations, many of whom are concentrated (along with infrastructure and agriculture) in drainage basins between the mountains.

Stressed Infrastructure

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise and coastal flooding, and intense precipitation events.

Disruptions to services provided by public and private infrastructure in the Northeast both interrupt commerce and threaten public health and safety. A 1.5 foot rise in sea level (1 to 4 feet are projected by 2100; Ch. 2: Our Changing Climate, Key Message 9) would expose approximately $6 trillion worth of property to coastal flooding in the Baltimore, Boston, New York, Philadelphia, and Providence metropolitan areas (Lenton et al. 2009). In New York alone, two feet of sea level rise is estimated to flood 212 miles of roads, 77 miles of rail, 3,647-acres of airport facilities, and 539-acres of runways, without substantial investments in adaptation (DOT 2008). Port facilities, such as in Maryland (primarily Baltimore), have similar estimates of flooding: 298 acres, or 32% percent of the overall port facilities in the state (DOT 2008). These impacts have potentially significant economic ramifications. For example, in 2006 alone the Port of Baltimore generated over 50,200 jobs, $3.6 billion in personal income, $1.9 billion in business revenues, and $388 million in state/county/municipal tax (Maryland Port Administration 2008). A broader range of impacts across economic sectors, drawn from the New York City Panel on Climate Change but applicable throughout the region, highlights some of the reality currently being faced in the aftermath of Hurricane Sandy and in the future.

Table 16.1. *Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig, (2010); Zimmerman and Faris, (2010)*

Communications	**Energy**	**Transportation**	**Water and Waste**
Higher average sea level			
• Increased salt water encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance costs and shortened replacement cycles • Cellular tower destruction or loss of function	• Increased rates of coastal erosion and/or permanent inundation of low-lying areas, threatening coastal power plants • Increased equipment damage from corrosive effects of salt water encroachment, resulting in higher maintenance costs and shorter replacement cycles	• Increased salt water encroachment and damage to infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, resulting in increased maintenance costs and shorter replacement cycles • Decreased clearance levels under bridges	• Increased salt water encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure • Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownfields, and waste storage facilities • Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations • Increased saltwater infiltration into freshwater distribution systems
More frequent and intense coastal flooding			
• Increased need for emergency management actions with high demand on communications infrastructure • Increased damage to communications equipment and infrastructure in low-lying areas	• Increased need for emergency management actions • Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action • Increased use of energy to control floodwaters • Increased number and duration of local outages due to flooded and corroded equipment	• Increased need for emergency management actions • Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to infrastructure due to wave action • Decreased levels of service from flooded roadways; increased hours of delay from congestion during street flooding episodes • Increased energy use for pumping	• Increased need for emergency management actions • Exacerbated street, basement, and sewer flooding, leading to structural damage to infrastructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

In the transportation sector, many of the region's key highways (including I-95) and rail systems (including Amtrak) span areas that are prone to coastal flooding. In addition to temporary service disruptions, saltwater damage associated with storm surge flooding can severely undermine or disable critical infrastructure along coasts, including subway systems, wastewater treatment plants, and electrical substations.

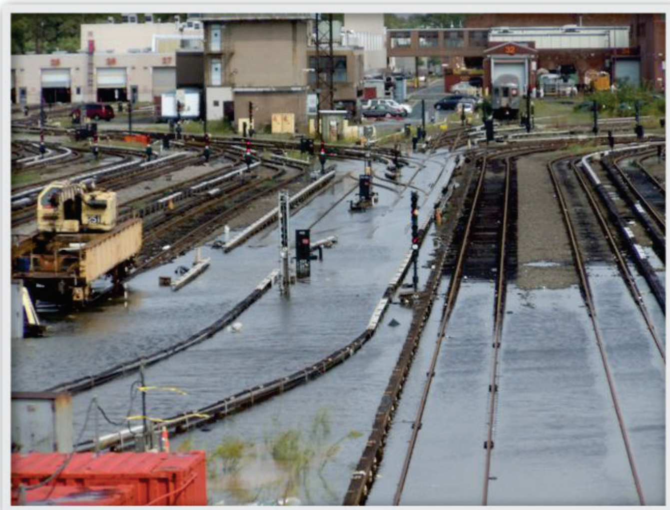

Figure 16.7

Caption: Flooded subway tracks in Coney Island after Hurricane Irene. (SOURCE: MTA (http://www.flickr.com/photos/mtaphotos/6089071863/sizes/o/in/photostream/)

Agricultural and Ecosystem Impacts

Agriculture and ecosystems will be increasingly stressed by climate-related hazards, including higher temperatures, sea level rise and coastal flooding, and more extreme precipitation events. A longer growing season may allow farmers to explore new crop options, but this and other adaptations will not be cost- or risk-free, and inequities exist in the capacity for adaptation.

Farmers in the Northeast are already experiencing consequences of climate change. In addition to direct crop damage from more intense precipitation events, wet springs delay planting for grain and vegetables, for example, and subsequently delay harvest dates and reduce yields (Ohlemeier 2011). This is an issue for agriculture nationally (Hatfield et al. 2011), but is particularly acute for the Northeast where heavy rainfall events have increased more than any other region of the country (Groisman et al. 2004). In the future, farmers may also face too little water in summer to meet increased crop water demand as summers become hotter and growing seasons lengthen (Hayhoe et al. 2007; Wolfe et al. 2011b). Increased frequency of summer heat stress is also projected, which can negatively affect crop yields and milk production (Wolfe et al. 2008).

Despite a trend toward warmer winters, the risk of frost and freeze damage continues, and has paradoxically increased over the past decade (See also Ch. 8: Ecosystems and Biodiversity).

Increased weed and pest pressure associated with longer growing seasons and warmer winters will be an increasingly important challenge; there are already examples of earlier arrival and increased populations of some insect pests such as corn earworm (Wolfe et al. 2008). Furthermore, many of the most aggressive weeds, such as kudzu, benefit more than crop plants from higher atmospheric carbon dioxide, and become more resistant to herbicide control (Ziska and Runion 2007).

Effects of rising temperatures on the Northeast's ecosystems have already been clearly observed (See also Ch. 8: Ecosystems and Biodiversity). Wildflowers (Abu-Asab et al. 2001) and woody perennials are blooming earlier (Primack et al. 2004; Wolfe et al. 2005) and migratory birds are arriving sooner (Butler 2003). Several bird species have expanded their ranges northward (Rodenhouse et al. 2009) as have some invasive insect species such as the hemlock wooly adelgid (Paradis et al. 2008), which has devastated hemlock trees. Warmer winters and less snow cover in recent years have contributed to increased deer populations (Wolfe et al. 2011a) that degrade forest understory vegetation (Stromayer and Warren 1997).

Although suitable habitats will be shrinking for some species (cold water fish such as brook trout) and expanding for others (warm water fish such as bass), it is difficult to predict what proportion of species will be able to move or adapt as their optimum climate zones shift (Jenkins 2010). As each species responds uniquely to climate change, disruptions of important species interactions (plants and pollinators, predators and prey) can be expected. For example, it is uncertain what form of vegetation will move into the Adirondack Mountains when the suitable habitat for spruce-fir forests disappears (Iverson et al. 2008). Increased productivity of some northern hardwood trees in the Northeast is projected (due to longer growing seasons and assuming a significant benefit from higher atmospheric carbon dioxide), but summer drought and other extreme events may override this potential (Mohan et al. 2009).

In contrast, many insect pests, pathogens, and invasive plants like kudzu appear to be highly and positively responsive to recent and projected climate change (Dukes et al. 2009). Their expansion will lead to an overall loss of biodiversity, function, and resilience of some ecosystems.

The Northeast's coastal ecosystems are also highly vulnerable to rising seas. For example, a five foot sea level rise through 2100 (within the range of the 6.6 foot scenario useful for risk-averse planning (Parris et al. 2012; Ch.2: Our Changing Climate; Key Message 9)) is projected to lead to the loss of over 93% of tidal marshes and swamps, and the inundation of over 32,000-acres within the Blackwater National Wildlife Refuge by 2100 (Maryland Department of Natural Resources 2008). Beach and dune erosion is also a major issue in the Northeast (Buonaiuto et al. 2011; Gornitz et al. 2001).

Box: The Chesapeake Bay

The Chesapeake Bay, with a drainage basin that extends over six states, is an example of a critical and highly integrated natural and economic system threatened by changing land use patterns and a changing climate – including sea level rise, higher temperatures, and more intense precipitation events. The ecosystem has a central role in the economy, including providing sources of food for people and the region's other inhabitants, and cooling water for the energy sector. It also provides critical ecosystem services.

Chesapeake Bay

Figure 16.8

(Source: NASA)

– end box --

Planning and Adaptation

While a majority of states and several municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Of the 12 states in the Northeast, 11 have developed adaptation plans for several sectors and 10 have released, or plan to release, statewide adaptation plans (Georgetown Climate Center 2012). Given the interconnectedness of climate change impacts and adaptation, multi-state coordination could help to ensure that information is shared efficiently and that emissions reduction and adaptation strategies do not operate at cross-purposes.

Local and state governments in the Northeast have been leaders and incubators in utilizing legal and regulatory opportunities to foster climate change policies (Sussman 2008). The Regional Greenhouse Gas Initiative (RGGI) was the first market-based regulatory program in the U.S. to reduce greenhouse gas emissions; it is a cooperative effort among nine northeastern states (RGGI 2011). Massachusetts became the first state to officially incorporate climate change impacts into its environmental review procedures by adopting legislation that directs agencies to “consider reasonably foreseeable climate change impacts, including additional greenhouse gas emissions, and effects, such as predicted sea level rise” (State of Massachusetts 2012).

Connecticut Coastline and Expanding Salt Marshes

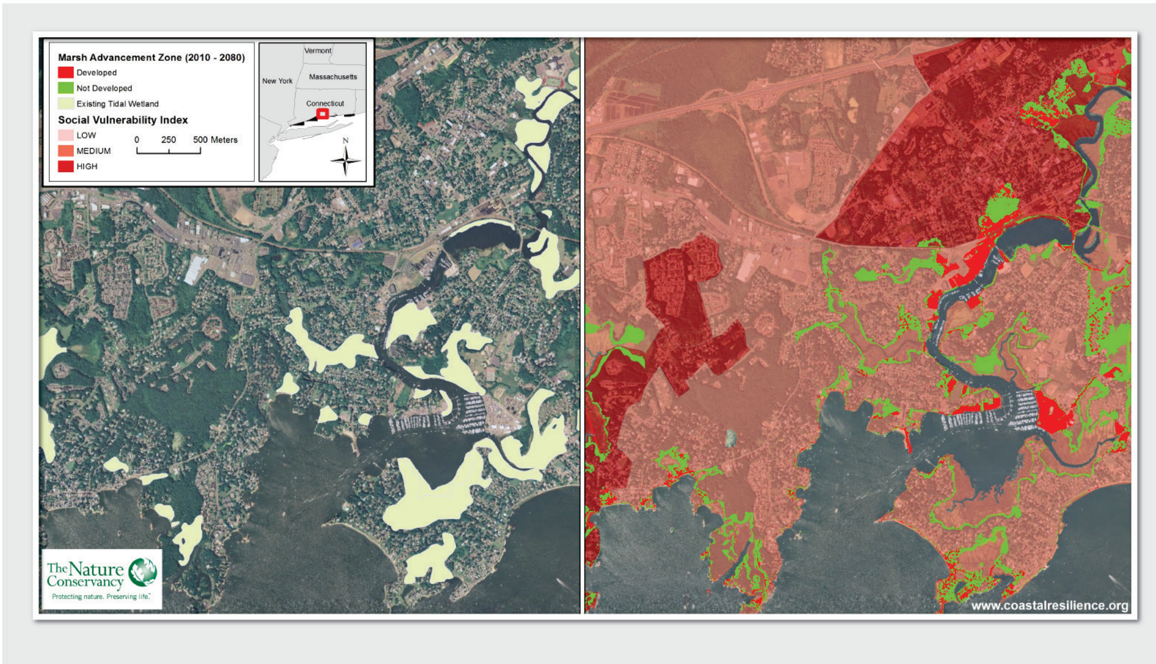

Figure 16.9: Connecticut Coastline and Expanding Salt Marshes

Caption: The Nature Conservancy's adaptation decision-support tool shows projected inundation of land along the Connecticut coast by the 2080s. The maps show both building-level impacts and potential marsh ecosystem responses as sea levels rise. (Source: The Nature Conservancy 2012)

Northeast cities have employed a variety of mechanisms to respond to climate change, including land use planning, provisions to protect infrastructure, regulations related to the design and construction of buildings, and emergency preparation, response, and recovery (see ORNL 2012). While significant progress has been made, local governments still face limitations of legal authority, geographic jurisdiction, and resource constraints that could be addressed through effective engagement and support from higher levels of government.

Keene, New Hampshire has been a pilot community for ICLEI's Climate Resilient Communities program for adaptation planning (Sussman 2009) – a process implemented through innovative community engagement methods (Engert 2010). New York City has taken numerous steps to implement PlaNYC, a far reaching sustainability plan for the city, including amending the construction code and the zoning laws and the implementation of measures focused on developing adaptation strategies to protect the City's public and private infrastructure from the effects of climate change (Rosenzweig et al. 2011a); some major investments in protection have even been conceptualized.

Figure 16.10

Caption: Conceptual Design of a Storm Surge Barrier in NYC. (Source: Aerts et al. 2009)

One well-known adaptation-planning tool is the eight-step iterative approach developed by the New York City Panel on Climate Change; it was highlighted in the contribution of the National Academy of Science's Adaptation Panel to America's Climate Choices and adopted by the Committee on America's Climate Choices. It describes a practical procedure that decision-makers at all levels can use (and have already begun to use, for example in support of the National Climate Assessment) to design a flexible adaptation pathway to address infrastructure and other response issues through inventory and assessment of risk. The key, with respect to infrastructure, is to link adaptation strategies with capital improvement cycles and adjustment of plans to incorporate emerging climate projections (Rosenzweig and Solecki 2010; Rosenzweig et al. 2011b) – but the insights are far more general than that (see the Adaptation Panel Report (NRC 2010).

In most cases, adaptation requires information and tools coupled to a decision-support process steered by strong leadership, and there are a growing number of examples in the Northeast. At the smaller municipal scale, coastal pilot projects in Maryland (Cole 2008; Maryland Department of Natural Resources 2008), Delaware (Delaware Coastal Programs 2011), New York and Connecticut (Ferdaña et al. 2010) are underway.

Figure 16.11

Caption: NASA facilities managers and climate scientists work together closely to plan appropriate adaptation strategies for their physical plant in response to hazard-specific local information and climate scenarios.

Research and outreach efforts are underway in the region to help farmers find ways to cope with a rapidly changing climate, take advantage of a longer growing season, and reduce greenhouse gas emissions (Wolfe et al. 2011b; Wolfe et al. 2011c), but inequities in farmer access to capital and information for strategic adaptation and mitigation remain a challenge.

Regional activities in the Northeast are also being linked to federal efforts. For example, NASA's Agency-wide Climate Adaptation Science Investigator Workgroup (CASI) brings together NASA facilities managers with NASA climate scientists in local Climate Resilience Workshops. This approach was in evidence at the Goddard Space Flight Center in Maryland, where scientists helped institutional managers address energy and stormwater management vulnerabilities.

Box: Culverts as Adaptation
Culverts, the ubiquitous, mostly out-of-sight large pipes that carry water under roads, trails, and embankments are constantly being built, replaced, or upgraded. In Maine, the State Department of Transportation manages over 97,000 culverts, but even more are managed by individual property owners or small towns; Scarborough, Maine, for example, has 2,127 culverts.

Culverts are increasingly being washed out during intense precipitation events; storms that used to occur once in 100 years in the 1950s through the 1970s occurred every 60 years during the recent 1978-2007 period (DeGaetano 2009). When 71 town managers and officials in coastal Maine were surveyed as part of the statewide Sustainable Solutions Initiative, culverts, with their 50-65 year expected lifespan, emerged atop a wish list for help in adapting to climate change.

By mapping town managers' decisions to the sources of climate information, engineering design, mandated requirements, and decision calendars, a culvert governance map from local to global scales emerged (Gray et al. 2012). The complexity of the map, and its many levels of governance, illustrates the challenge of widespread adaptation for even such simple actions as using larger culverts. To help towns adapt culverts to expected climate change over their lifetimes, the Sustainability Solutions Initiative is creating decision tools to map culvert locations, schedule maintenance, estimate needed culvert size, analyze replacement needs and costs, and identify funding sources, their application forms, and calendars.

-- end box --

Traceable Accounts

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Key Message Process: Results of the NE Regional Climate assessment workshop that was held on November 17th and 18th, 2011 at Columbia University, with approximately 60 attendees - the beginning of the process that lead to the foundational Technical Input Report (TIR) report (Horton et al. 2012) – were critically important in our assessment. That 313-page report consisted of 7 chapters by 13 Lead authors and more than 60 authors in total. Public and private citizens or institutions who service and anticipate a role in maintaining support for vulnerable populations in NE Region cities and communities indicated that they are making plans to judge the demand for adaptation services. These interactions were surveyed and engaged in the preparation of this chapter, because we are confident that the TIR authors made a vigorous attempt to engage various agencies at the state level and NGO's who have broader perspectives.

The author team engaged in multiple technical discussions via teleconferences, which included careful review of the foundational TIR (Horton et al. 2012) and approximately 50 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the lead author of each subset of this key message.

Key message #1/4	**Heat waves, coastal flooding due to sea level rise, and river flooding due to more extreme precipitation events will add stresses to the region's already burdened environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially populations that are already most disadvantaged.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the NE Technical Input Horton et al (2012). Nearly 50 Technical Input reports, on a wide range of topics, were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications (including many that are not cited) describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation for the Northeast. For sea level rise, the authors relied on the NCA SLR scenario (Parris et al. 2012) and experience on the topic (e.g., Horton and Rosenzweig 2010). Recent work by Gaffin et al. (2008) summarizes the literature on heat islands and extreme events, and Kunkel et al. (2012) worked closely with the region's state climatologists on both the climatology and projections. Many relevant and recent peer-reviewed publications (Anderson and Bell 2012; Crowell et al. 2010; EPA 2006; Huang et al. 2011; Knowlton et al. 2007; Sheffield et al. 2011b; Solecki et al. 2011) that describe how human vulnerabilities to climate hazards in the region can be augmented by socio-economic and other factors were also considered. Evaluating coupled multi-system vulnerabilities is an emerging field; as a result, additional sources including white papers have informed this major message as well. Various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) or Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf) to capture key issues, concerns and opportunities in the region.
New information and remaining	Important new evidence (cited above) confirmed many of the findings from a prior Northeast assessment; see

uncertainties	(http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/northeast). This evidence included results from improved models and updated observational data, and the assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm it relevance and significance for local decision-makers. There is wide diversity of impacts across the region driven by both exposure and sensitivity that are location and socio-economic context specific. Future vulnerability will be influenced by changes in demography, economics, and policies (development, economic, and climate driven) that are difficult to predict and dependent on international and national considerations. Another uncertainty is the potential for adaptation strategies (and to a lesser extent mitigation and geoengineering) to reduce these vulnerabilities. There are also uncertainties associated with the character of the interconnections and the positive and negative synergies. For example, a key uncertainty is how systems will respond during extreme events (climatically and otherwise) and adjust their short to long-term planning to take account of a dynamic climate, since such events are by definition, manifestations of historically rare and therefor relatively undocumented climatology but nonetheless correlated, when considered holistically, with dynamic climate change driven to some degree by human interference with the climate system; these are the uncertainties in exposure. There are also uncertainties associated with sensitivity to future changes driven in to some (potentially significant) degree by non-climate stressors, including background health of the human population and development decisions. Other uncertainties include how much effort will be put into making systems more resilient, and their success.
Assessment of confidence based on evidence	**Very high** for sea level rise and coastal flooding as well as heat waves **High** for intense precipitation events and riverine flooding. **Very high** confidence for both added stresses on systems and for increased vulnerability, esp. those most disadvantaged.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #2/4	**Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise and coastal flooding, and intense precipitation events.**
Description of evidence base	The text summarizes extensive evidence documented in the NE Technical Input (Horton et al. 2012). Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) or Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf) to capture key issues, concerns and opportunities in the region. In addition, the cited DOT (2008) report provided extensive documentation that augmented Lenton et al. (2009), but this is an NGO publication with an uncertain review process. Nonetheless, all of these sources supported this key message.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Northeast assessment: (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/northeast). These new sources relied on improved models that have been calibrated to new observational data across the region. It is important to note, of course, that there is wide diversity across the region because both exposure and sensitivity are location and socio-economic context specific. The conventional wisdom derived from many previous assessments by the National Academies, the New York Panel on Climate Change, and the Intergovernmental Panel on Climate Change indicates that future vulnerability at any specific location will be influenced by changes in demography, economics, and policy that are difficult to predict at local scales even as they depend on international and national considerations. The potential for adaptation strategies (and to a lesser extent mitigation and geoengineering) to reduce these vulnerabilities is yet another source of uncertainty that expands as the future moves into the middle of this century.
Assessment of confidence based on evidence	Based on our review of the literature and submitted input and defended internally and externally in conversation with local decision-makers and representatives of interested NGO's (as well as the extensive interactions across the region reported in NE Technical Input (TIR) noted above, we have **very high** confidence for sea level rise and coastal flooding, and high confidence for intense precipitation events. **Very high** confidence for added stresses on infrastructure is based on the clear evidence of impacts on current infrastructure from hazards such as Hurricane Irene (see text), and from the huge deficit of needed renewal identified by a diverse engineering community.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/4	**Agriculture and ecosystems will be increasingly stressed by climate-related hazards, including higher temperatures, sea level rise and coastal flooding, and more extreme precipitation events. A longer growing season may allow farmers to explore new crop options, but this and other adaptations will not be cost- or risk-free, and inequities exist in the capacity for adaptation.**
Description of evidence base	The text again summarizes extensive evidence documented in the NE Technical Input (Horton et al. 2012). Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Please consult the Traceable Account documentation for our first key message for evidence base on sea level rise, flooding and precipitation. Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region with particular focus on managed (agriculture) and unmanaged (ecosystems) systems. Species and ecosystem vulnerability have been well documented historically in numerous peer-reviewed papers in addition to the ones cited in this key message (See Horton et al. 2012). There have also been many examples of agricultural impacts of climate variability and change in the Northeast, although most note that there is potential for significant benefits associated with climate changes to partially offset expected negative outcomes for these managed systems.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior Northeast assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/northeast). These new sources also relied on improved models that have been calibrated to new observational data across the region. Both agriculture and ecosystems in the Northeast are strongly linked to climate and other changes occurring outside the region and beyond the boundaries of the United States. These changes can influence the price of crops and agricultural inputs such as fertilizer, for example, as well as the abundance of ecosystem and agricultural pests. Other uncertainties include imprecise understandings of how complex ecosystems will respond to climate and non-climate induced changes, and the extent to which organisms may be able to adapt to a changing climate.
Assessment of confidence based on evidence	Based on our assessment and defended among ourselves and external experts, we have **very high** confidence for climate impacts (especially SLR and storm surge) on ecosystems; and we have **high** confidence for climate impacts on agriculture (ameliorated so some degree by uncertainty about the efficacy and implementation of adaptation options).

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #4/4	**While a majority of states and several municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.**
Description of evidence base	The text again relies heavily on extensive evidence documented in the NE Technical Input (Horton et al. 2012). Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Many of the key references cited reflected experiences and processes developed in iterative stakeholder engagement concerning risk management (Rosenzweig et al. 2011b; Rosenzweig et al. 2009) that have been heavily cited and employed in new venues – local communities like Keane (NH) and New York City, for example. Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region. In addition, there have been agency and government white paper reports describing proposed adaptation strategies based on climate impact assessments. We discovered that ten of the 12 states in the Northeast have statewide adaptation plans in place or under development.
New information and remaining uncertainties	That most NE states have begun to plan for adaptation is a matter of record. That few adaptation plans have been implemented is confirmed in submissions to the National Climate Assessment process as well as prior assessments. See, for example, (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/northeast). Key uncertainties in looking forward include: 1) the extent to which proposed adaptation strategies will be implemented given a range of factors including competing demands and limited funding, 2) the role of the private sector and individual action in adaptation, which can be difficult to document, 3) the extent of the federal role in adaptation planning and implementation in the future, and 4) how changes in technology and the world economy may change the feasibility and attractiveness of specific adaptation strategies.
Assessment of confidence based on evidence	This KM is simply a statement of observed fact, so confidence language is not applicable.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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17. Southeast and the Caribbean

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Key Messages

1. **Sea level rise poses widespread and continuing threats to both natural and built environments, as well as the regional economy.**
2. **Rising temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.**
3. **Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and impact the region's economy and unique ecosystems.**

Introduction

The Southeastern region is exceptionally vulnerable to sea level rise, extreme heat events, and decreased water availability. The spatial distribution of these impacts and vulnerabilities is uneven, since the region encompasses a wide range of natural-system types, from the Appalachian Mountains to the coastal plains. It is also home to more than 80 million people, and draws hundreds of million visitors every year (U.S. Census Bureau 2010) .

The region has one of the most populous metropolitan areas in the country (Miami) and four of the ten fastest-growing such areas (U.S. Census Bureau 2010). Three of these (Palm Coast, FL, Cape Coral-Fort Meyers, FL, and Myrtle Beach area, SC) are along the coast and vulnerable to sea level rise and storm surge.

The Gulf and Atlantic coasts are major producers of seafood and home to seven major ports (Ingram et al. 2012) that are also vulnerable. The Southeast is a major energy producer of coal, crude oil, and natural gas, and the highest energy user of any of the National Climate Assessment regions (Ingram et al. 2012).

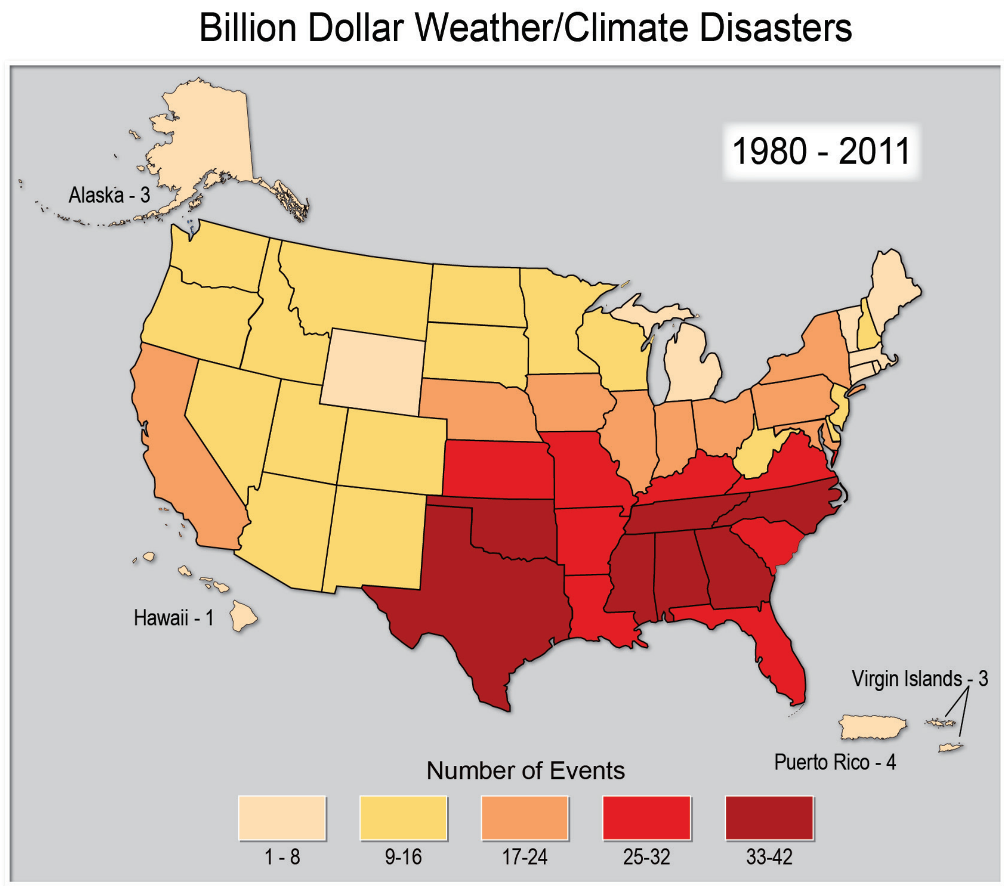


Figure 17.1: Billion Dollar Weather/Climate Disasters 1980-2011.

Caption: This map summarizes the number of weather and climate disasters over the past 30 years that have resulted in more than a billion dollars in damages. The Southeast has experienced more billion-dollar disasters than any other region.

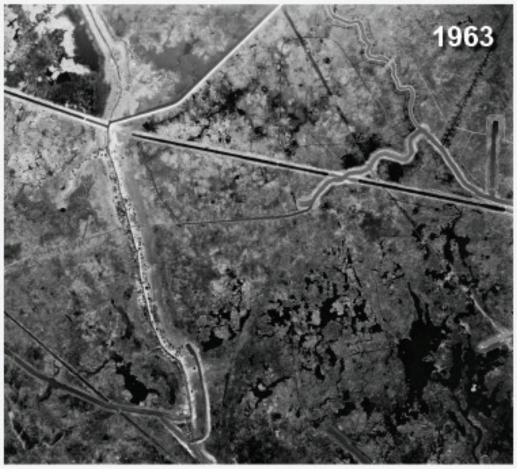
http://www.ncdc.noaa.gov/billions/Population Distribution and Change: 2000 to 2010, summary statistics

The Southeast's climate is influenced by many factors, including latitude, topography, and proximity to large bodies of water like the Atlantic Ocean and the Gulf of Mexico. Temperatures generally decrease northward and into mountain areas, while precipitation decreases with distance from the Gulf and Atlantic coasts. Its climate also varies considerably over seasons, years, and decades, largely due to natural cycles such as the El Niño-Southern Oscillation (ENSO, periodic changes in ocean surface temperatures in the Tropical Pacific Ocean), the semi-permanent high pressure system over Bermuda, differences in atmospheric pressure among key areas of the globe, and land-falling tropical weather systems (Katz et al. 2003; Kunkel et al. 2006; Kutzman and Scanlon 2007; Li et al. 2011; Misra et al. 2011). These cycles contribute to occurrences of droughts, flooding, freezing winters, hurricane wind damage, and property damage from tornadoes.

Box: Stories of Change: Coastal Louisiana Tribal Communities

Four Native Communities in Southeast Louisiana (Grand Bayou Village, Grand Caillou/Dulac, Isle de Jean Charles, and Pointe-au-Chien) have already experienced land loss from river management that has deprived the coastal wetlands of the freshwater and sediment that it needs to survive. As a result of this and other natural and man-made problems, Louisiana has lost 1,880 square miles of land in the last 80 years (Louisiana's 2012 Coastal Master Plan). Numerous other impacts from increases in temperature, sea level rise, land loss, erosion, subsidence, and salt-water intrusion amplify this main problem. This combination of changes has resulted in a cascade of losses of sacred places, healing plants, habitat for important wildlife (such as eagles), food security (from lack of land and water to grow food), and of connectivity with the mainland. Additional impacts include increased inundation of native lands, further travel to reach fishing grounds, reduced connections among family members as their lands have become more flood-prone, and declining community cohesiveness as heat requires more indoor time (Coastal Louisiana Tribal Communities 2012).

Isle de Jean Charles



1963 aerial photograph of Isle de Jean Charles, LA - not retouched or recolored. Island Road, the lone roadway that leads to the narrow Isle de Jean Charles, was built ten years prior to this photograph. Families have lived on the ridge of higher ground since the 19th century, but in this photo a significant amount of marsh still remains.

2008 aerial photograph of Isle de Jean Charles, LA. By the time this image was taken, Louisiana and the surrounding Gulf Coast had been pummeled by four major Hurricanes- Katrina, Rita, Ike and Gustav. With marshland weakened by the loss of water and sediment, development, canals, erosion, and higher sea levels, the storms surged further inland. The Terrebonne Basin didn't bear the brunt of these storms, but it still experienced damage with little time to recover between the disasters.

Figure 17.2

Photos courtesy of USGS.

—end box –

Observed and Projected Climate Change

Average annual temperature during the last century across the Southeast cycled between warm and cool periods (see figure below, black line), with a warm peak occurring during the 1930s and 40s followed by a cool period in the 60s and 70s, and warming again from 1970 to the present by an average of 2°F, with more warming on average during summer months. There have been increasing numbers of days above 95°F and nights above 75°F, and decreasing numbers of extremely cold days since 1970 (Kunkel et al. 2012). Daily and five-day rainfall intensities have also increased (Ingram et al. 2012), as summers have been either increasingly dry or extremely wet (Kunkel et al. 2012). Better reporting of major tornados makes it appear that they have increased over the last 50 years; however there has been no actual statistically significant trend (Verbout et al. 2006). The number of Atlantic-basin hurricanes has increased slightly during the last 130 years, and Category 4 and 5 hurricanes have increased since the 1970s (Knutson et al. 2010; Ch. 2: Our Changing Climate; Key Message 8). This can be attributed to both natural variability and climate change.

Southeast Temperature: Observed and Projected

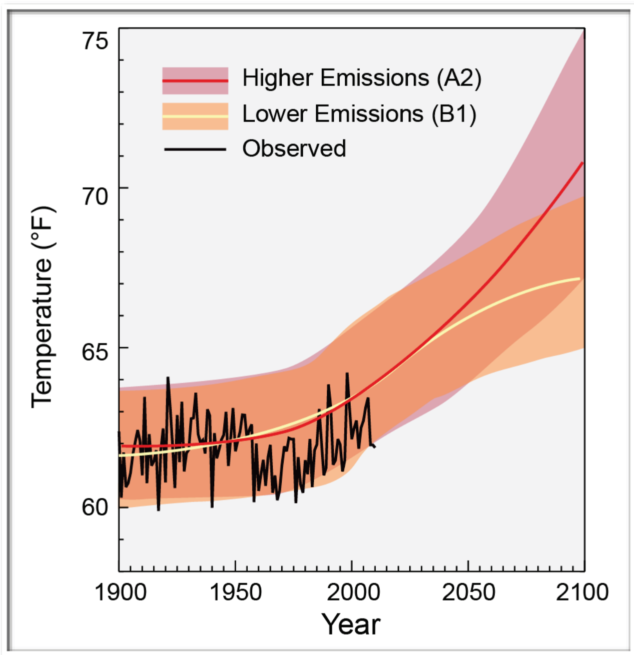


Figure 17.3: Southeast Temperature: Observed and Projected

Caption: Observed annual average temperature for the Southeast (black) and projected assuming substantial emissions reductions (lower emissions, B1) and assuming continued growth in emissions (higher emissions, A2) (Kunkel et al. 2012). For each emissions scenario, shading shows the range of projections and the line shows a central estimate.

Temperatures across the Southeast are expected to increase during this century, fluctuating over time because of natural climate variability (annually and decade-to-decade) (Ch. 2: Our Changing Climate, Key Message 3). Major consequences of warming include significant increases in the number of hot days (95°F) and decreases in freezing events. Projections for the region by 2100 include increases of 10°F for interior states of the region, 2°F to 4°F for the Caribbean, and a regional average range of 2°F to 6°F (Kunkel et al. 2012).

Projections of future precipitation patterns are less certain than projections for temperature increases (Kunkel et al. 2012). Average changes in annual precipitation under a higher emissions scenario (A2) by later this century range from a nearly 10% reduction in the far southern and western portions of the region – with most of that reduction in the summer – to about 5% increases in the northeastern part of the region (Kunkel et al. 2012);(Ch. 2: Our Changing Climate, Key Message 5). Projections further suggest that warming will cause tropical storms to be fewer in number globally, but stronger in force, with more category 4 and 5 storms (Knutson et al. 2010).

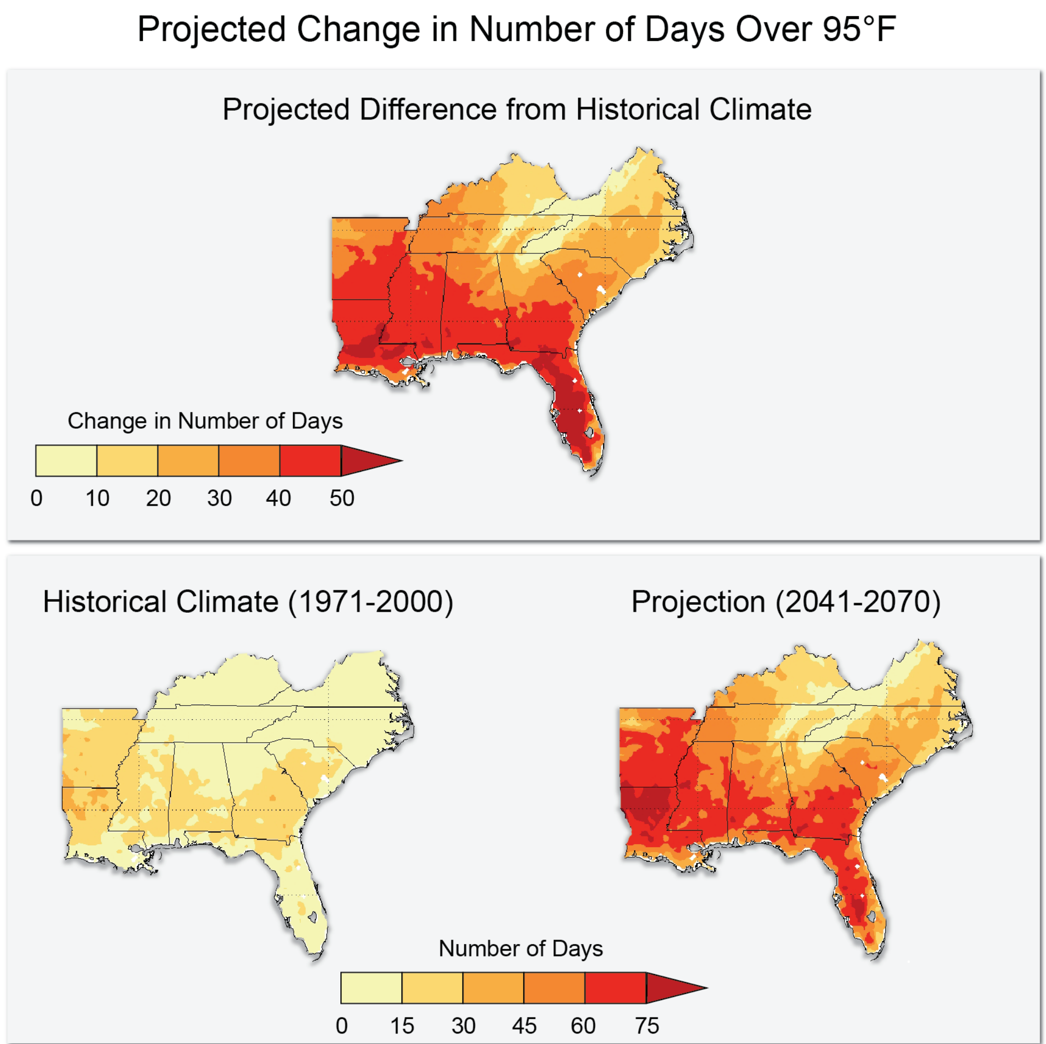


Figure 17.4: Projected Days Over 95°F

Caption: Projected number of days per year with maximum temperatures above 95°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario) (Kunkel et al. 2012).

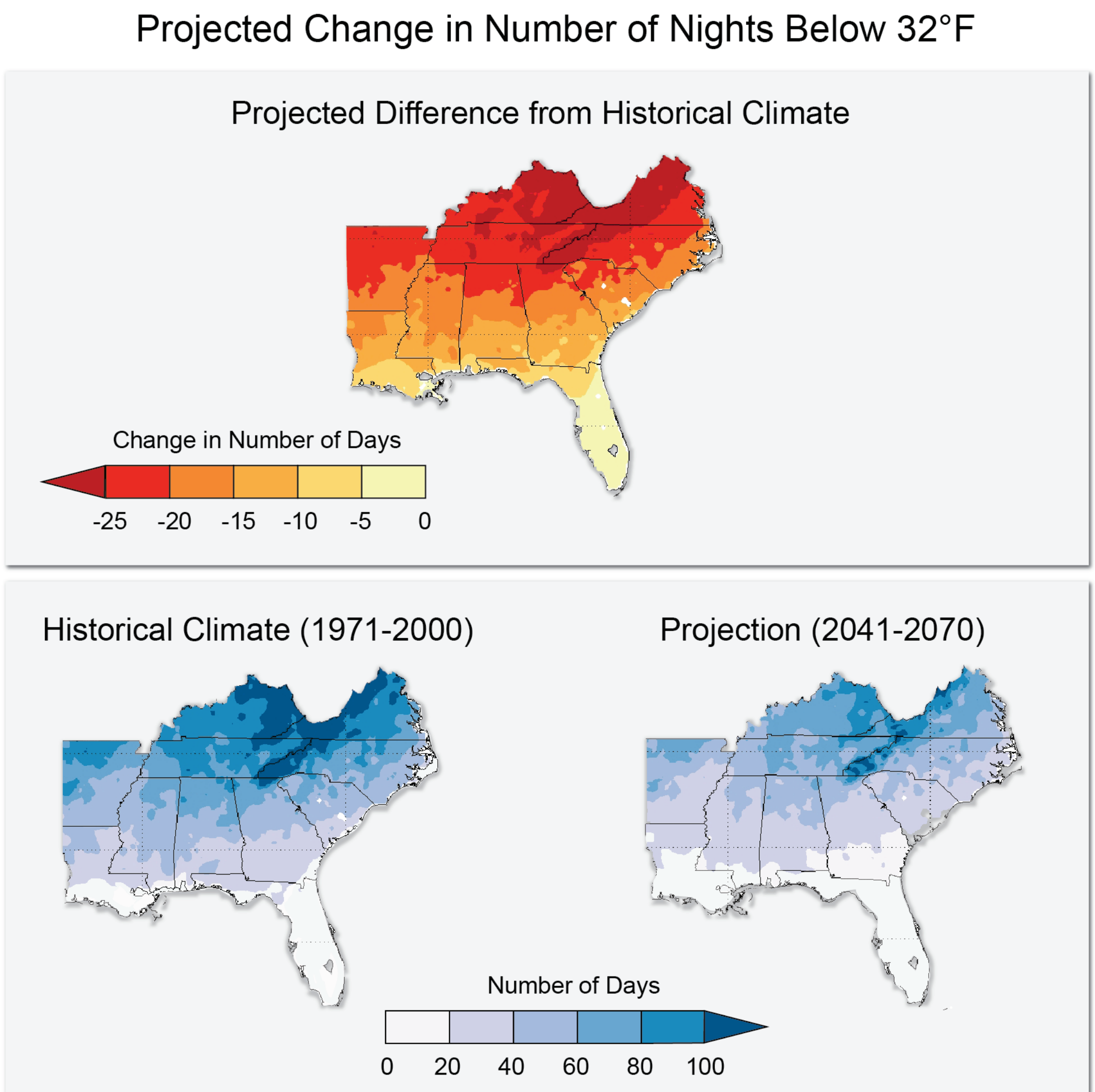


Figure 17.5: Projected Nights Below 32°F

Caption: Projected annual number of days with temperatures less that 32°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). (Kunkel et al. 2012).

Sea Level Rise Threats

Sea level rise poses widespread and continuing threats to both natural and built environments, as well as the regional economy.

Global sea level rise over the 20th century averaged approximately eight inches (Karl et al. 2009; Mitchum 2011; Ch. 2: Our Changing Climate; Key Message 9), and that rate is expected to accelerate through the end of this century (Parris et al. 2012). Portions of the Southeast are highly vulnerable to sea level rise, although how much sea level rise is experienced in any particular place depends on whether and how much the local land is sinking (also called subsidence) or rising, and changes in offshore currents (Sallenger et al. 2012).

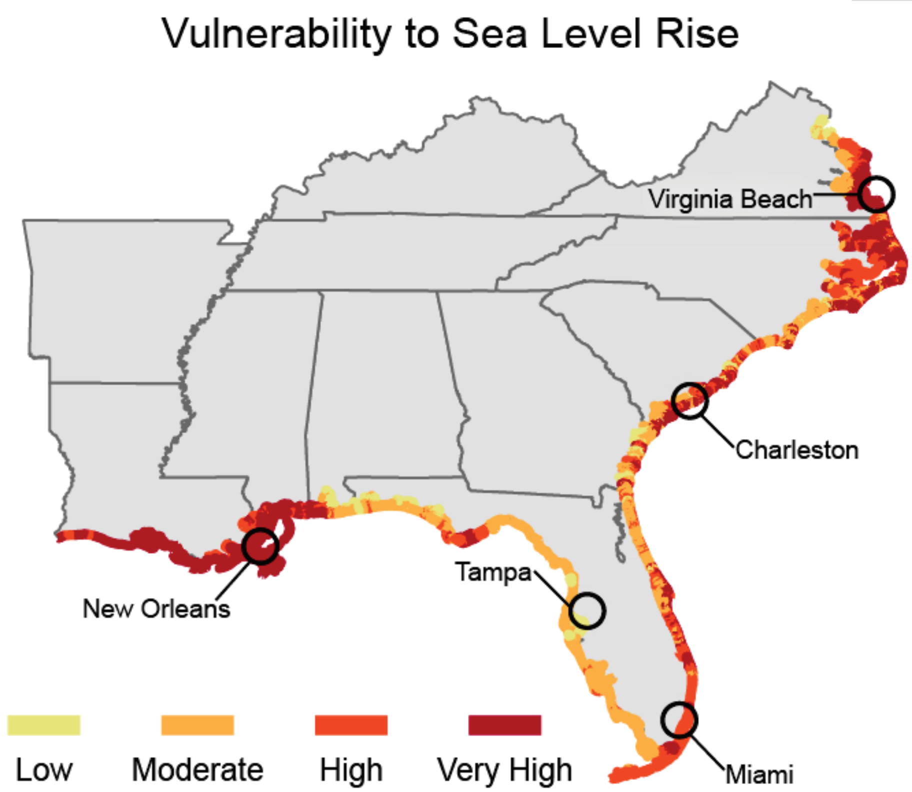


Figure 17.6: Vulnerability to Sea Level Rise

Caption: The map shows the relative risk that physical changes will occur as sea level rises. The Coastal Vulnerability Index used here is calculated based on tidal range, wave height, coastal slope, shoreline change, landform and processes, and historical rate of relative sea level rise. The approach combines a coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and yields a relative measure of the system's natural vulnerability to the effects of sea level rise (Hammar-Klose and Thieler 2001).

Large numbers of cities, roads, railways, ports, airports, oil and gas facilities, and water supplies are at low elevations and potentially vulnerable to the impacts of sea level rise. Major cities like

New Orleans, with roughly half of its population living below sea level (Campanella 2010), Miami, Tampa, Charleston, Virginia Beach, and San Juan, Puerto Rico are among those most at risk (Strauss et al. 2012). According to a recent study by the regional utility, Entergy, coastal counties and parishes in Alabama, Mississippi, Louisiana, and Texas, with a population of approximately 12 million, assets of about $2 trillion, and producers of $634 billion in annual GDP, already face significant losses that annually average $14 billion from hurricane winds, land subsidence, and sea level rise. Future losses for the 2030 timeframe could reach $18 billion (with no sea level rise or change in hurricane wind speed) to $23 billion (with nearly 3% increase in hurricane wind speed and just under 6 inches of sea level rise). Approximately 50% of the increase in the estimated losses is related to climate change. Entergy identified $7 billion in cost-effective adaptation investments that could reduce the 2030 losses by about 30% (Entergy et al. 2010).

The North Carolina Department of Transportation is raising the roadbed of U.S. Highway 64 by four feet, which includes 18 inches to allow for higher future sea levels (Devens 2012; Henderson 2011; Titus 2002). Louisiana State Highway 1, heavily used for delivering critical oil and gas resources from Port Fourchon, is "literally sinking" and now increasingly floods during high tides and low-level storms (Louisiana Department of Transportation and Development ; Louisiana's 2012 Coastal Master Plan 2012). The Department of Homeland Security (July 2011) estimated that a 90-day shutdown of this road would cost the nation $7.8 billion.

Highway 1 to Port Fourchon:
Vulnerability of a Critical Link for U.S. Oil

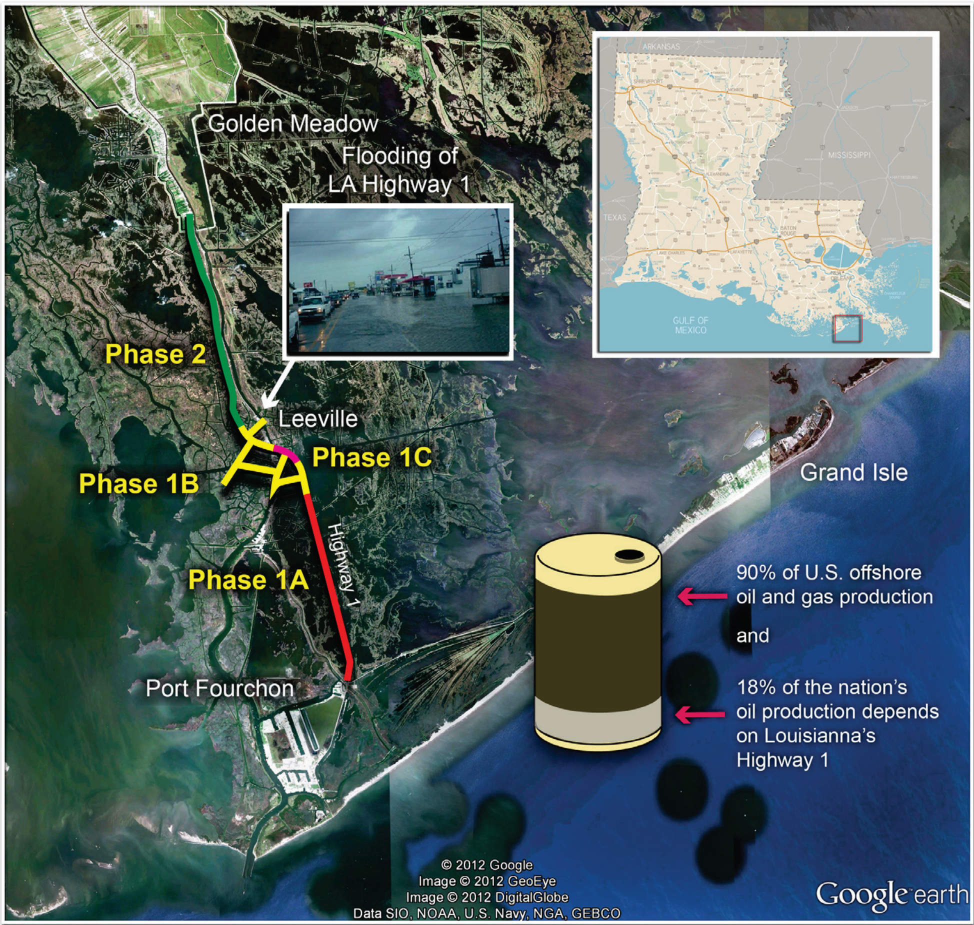


Figure 17.7: Highway 1 to Port Fourchon: Vulnerability of a Critical Link for U.S. Oil

Caption: Highway 1 in southern Louisiana is the only road to Port Fourchon, whose infrastructure supports 18% of the nation's oil and 90% of the nation's offshore oil and gas production. Flooding is becoming more common on Highway 1 in Leeville, (photo from flooding in 2004) on the way to Port Fourchon.

(Sources: Louisiana Department of Transportation and Development ; Louisiana's 2012 Coastal Master Plan 2012)

Sea level rise increases pressure on utilities, water, and energy, for example, by contaminating potential freshwater supplies with salt water, and such problems are amplified during extreme dry events with little run-off. Although uncertainties in the scale, timing, and location of climate change impacts can make decision-making difficult, response strategies can be effective with early planning. Some utilities in the region are already taking sea level rise into account in the construction of new facilities and are seeking to diversify their water sources (Heimlich et al. 2009).

As temperatures and sea levels increase, changes in marine and coastal systems are expected to affect the potential for energy resource development in coastal zones and the outer continental shelf. Oil and gas production infrastructure in embayments that are protected by barrier islands, for example, are likely to become increasingly vulnerable to storm surge as sea level rises and barrier islands deteriorate along the central Gulf coast. The capacity for expanding and maintaining onshore and offshore support facilities and transportation networks is also apt to be affected (Burkett 2011).

Sea level rise and storm surge can have impacts far beyond the area directly affected. Homes and infrastructure in low areas are increasingly prone to flooding during tropical storms. As a result, insurance costs will increase and people will move from vulnerable areas, stressing the social and infrastructural capacity of surrounding areas. This migration also happens in response to extreme events such as Hurricane Katrina, when more than 200,000 migrants were temporarily housed in Houston and 42% indicated they would try to remain there (Coker 2006).

Ecosystems of the Southeast are exposed to and at risk from sea level rise, especially tidal marshes and swamps. Some tidal freshwater forests are already retreating, while mangrove forests (adapted to coastal conditions) are expanding landward (Doyle et al. 2010). The pace of sea level rise will increasingly lead to inundation of coastal wetlands in the Southeast. Such a crisis in land loss has occurred in coastal Louisiana for several decades (Couvillion et al. 2011), with 1,880 sq. miles having been lost since the 1930s as a result of natural and man-made factors (Louisiana's 2012 Coastal Master Plan 2012). With tidal wetland loss, protection of coastal lands and people against storm surge will be compromised.

In some southeastern coastal areas, changes in salinity and water levels due to sea level rise can happen so fast that local vegetation cannot adapt quickly enough and those areas become open water (Nicholls et al. 2007). Fire, hurricanes, and other disturbances have similar effects, causing ecosystems to cross thresholds at which dramatic changes occur over short time frames (Burkett 2008; Burkett et al. 2005).

The impacts of sea level rise on agriculture derive from decreased freshwater availability, land loss, and saltwater intrusion. Salt-water intrusion is projected to reduce the availability of groundwater for irrigation, thereby limiting crop production in some areas (Ritschard et al. 2002). Agricultural areas around Miami-Dade County and southern Louisiana with shallow groundwater tables are at risk of enhanced inundation and future loss of cropland with a projected loss of 37,500 acres in Florida with a 27-inch sea level rise (Stanton and Ackerman 2007), which is well within a 1 to 4 foot range of sea level rise by 2100 (Ch. 2: Our Changing Climate, Key Message 9).

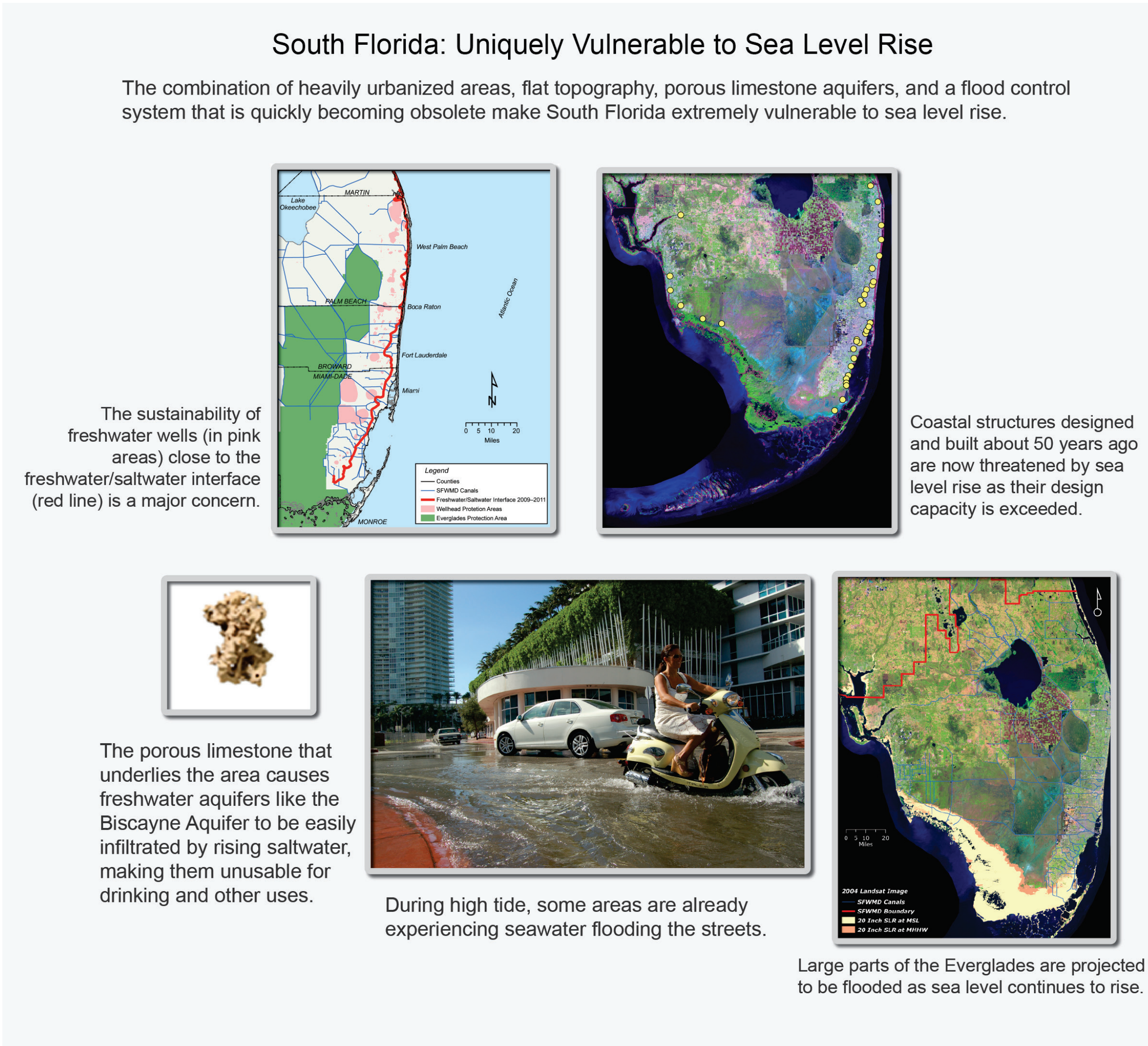


Figure 17.8

There are basically three types of adaptation options to rising sea levels: protect, accommodate, and retreat (Karl et al. 2009; Nicholls et al. 2007). Individuals and communities are using all of these strategies. However, regional cooperation among local, state, and federal governments can greatly improve the success of adapting to impacts of climate change and sea level rise. An excellent example is the Southeast Florida Regional Compact. Through collaboration of county, state, and federal agencies, a comprehensive action plan was developed that includes hundreds of actions and special Adaptation Action Areas (SFRCCC 2012).

Local Planning

Figure 17.9: Local Planning

Caption: Miami-Dade County staff leading workshop on incorporating climate change considerations in local planning. (Photo credit: Armando Rodriguez/Miami-Dade County)

Extreme Heat

Rising temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

The negative effects of heat on human cardiovascular, cerebral, and respiratory systems are well established (e.g., Kovats and Hajat 2008; O'Neill and Ebi 2009). Atlanta, Miami, New Orleans, and Tampa have already had increases in the number of days with temperatures exceeding 95ºF, during which the number of deaths is above average (Sheridan et al. 2009). By 2100, the Southeast is expected to have the highest increase in heat index (a measure of comfort that combines temperature and relative humidity) of any region of the country (Burkett et al. 2001). Higher temperatures also contribute to the formation of harmful air pollutants and allergens (Portier et al. 2010). Ground-level ozone is projected to increase in the 19 largest urban areas of the Southeast, leading to an increase in deaths (Chang et al. 2010). A rise in hospital admissions due to respiratory illnesses, emergency room visits for asthma, and lost school days is expected (Tagaris et al. 2009).

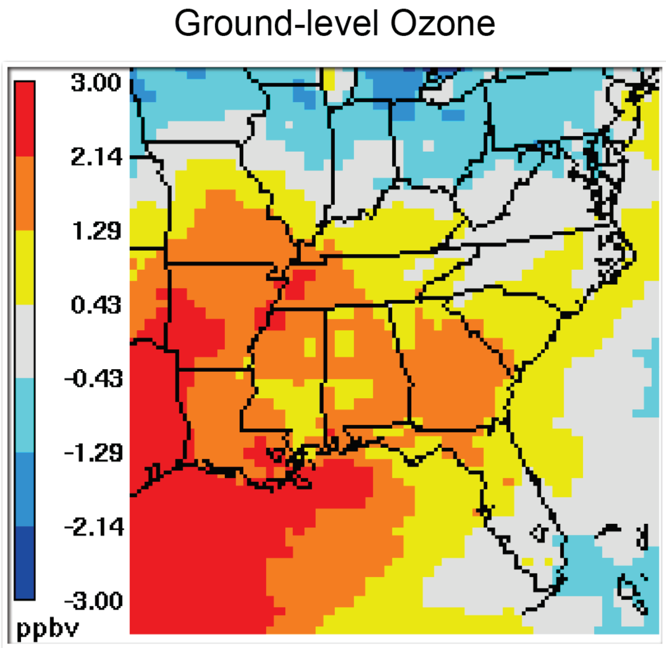


Figure 17.10: Ground-level Ozone

Caption: Ground-level ozone is an air pollutant that is harmful to human health and which generally increases with rising temperatures. The map shows projected increases in ground level ozone pollution in 2050 as compared to 2001, using a mid-range emissions scenario (A1B, assuming some decrease from current emissions growth trends). (Adapted from Tagaris et al. 2009)

The climate in many parts of the Southeast is suitable for mosquitoes carrying malaria, and yellow and dengue fevers. It is still uncertain how regional climate changes will impact vector-borne and zoonotic (animal to human) disease transmissions. While higher temperatures are likely to shorten both development and incubation time (Watts et al. 1987), vectors also need the right conditions for breeding (water), for dispersal (vegetation and humidity), and access to susceptible vertebrate hosts to complete the disease transmission cycle (Ingram et al. 2012). While these transmission cycles are complex, increasing temperatures have the potential to result in an expanded region with more favorable conditions for transmission of these diseases (CDC 2010; Filler et al. 2006; Mali et al. 2012).

Climate change is expected to increase harmful algal blooms and several disease-causing agents in inland and coastal waters, which were not previously problems in the Southeast (Hallegraeff 2010; Moore et al. 2008; Tester et al. 2010; Tirado et al. 2010; Wiedner et al. 2007). For instance, higher sea surface temperatures are associated with higher rates of ciguatera fish poisoning (Hales et al. 1999; Tester et al. 2010), one of the most common hazards from algal blooms in the region (Landsberg 2002). The algae that causes this food-borne illness is moving northward, following increasing sea surface temperatures (Litaker et al. 2010; Villareal et al. 2006). Certain species of bacteria (*Vibrio,* for example) that grow in warm coastal waters and are present in Gulf Coast shellfish can cause infections in humans. Infections are now frequently reported both earlier and later by one month than traditionally observed (Martinez-Urtaza et al. 2010).

Coral reefs in the Southeast, as well as worldwide, are susceptible to climate change, especially warming waters and ocean acidification, whose impacts are exacerbated when coupled with other stressors including disease, runoff, over-exploitation, and invasive species (Ingram et al. 2012). The region's aquaculture industry is also expected to be compromised by climate-related stresses (Twilley et al. 2001).

An expanding population and regional land-use changes have affected land available for agriculture and forests faster in the Southeast than in any other region (Loveland et al. 2012). Climate change is also expected to change the unwanted spread and locations of some nonnative plants, which will result in new management challenges (Hellmann et al. 2008).

Heat stress adversely affects dairy and livestock production (West 2003) – optimal temperatures for milk production are between 40ºF and 75ºF – and additional heat stress could shift dairy production northward (Fraisse et al. 2009). A 10% decline in livestock yield is projected across the Southeast with a 9ºF increase in temperatures (applied as an incremental uniform increase in temperature between 1990 and 2060), related mainly to warmer summers (Adams et al. 1999).

Summer heat stress is projected to reduce crop productivity, especially when coupled with increased drought. The 2007 drought cost the Georgia agriculture industry $339 million in crop losses (CIER 2009), and the 2002 drought cost North Carolina $398 million (Ingram et al. 2012). A 2.2ºF increase in temperature would likely reduce overall productivity for corn, soybeans, rice, cotton, and peanuts across the South – though rising CO_2 levels could partially offset these decreases (Hatfield et al. 2008), based on a crop yield simulation model. In Georgia, climate projections indicate corn yields could decline by 15% and wheat yields by 20% through 2020 (Alexandrov and Hoogenboom 2000). In addition, many fruits from long-lived trees and bushes require chilling periods and may need to be replaced in a warming climate (Hatfield et al. 2008).

Adaptation for agriculture involves decisions at many scales, from infrastructure investments (like reservoirs) to management decisions (like cropping patterns) (Howden et al. 2007). Dominant adaptation strategies would include altering local planting choices to better match new climate conditions (Howden et al. 2007) and developing heat-tolerant crop varieties and breeds of livestock (Fraisse et al. 2009; Ingram et al. 2012). Most critical for effective adaptation is the delivery of climate risk information to decision-makers at appropriate temporal and spatial scales (Fraisse et al. 2009; Howden et al. 2007), and focus on cropping systems that increase water use efficiency, shifts toward irrigation, and more precise control of irrigation delivery (Fraisse et al. 2009; Ingram et al. 2012).

The Southeast (includes Texas and Oklahoma, not Puerto Rico) leads the nation in number of wildfires, averaging 45,000 fires per year (Gramley 2005), and this number continues to increase (Morton et al. 2012; Stanturf and Goodrick 2012). Increasing temperatures contribute to increased fire frequency, intensity, and size (Gramley 2005). Lightning, a frequent initiator of wildfires, is expected to increase (Wu et al. 2008). Drought often correlates with large wildfire events, as seen with the Okeefenokee (2007) and Florida fires (1998). The 1998 Florida fires led to losses of more than $600 million (Butry et al. 2001). Wildfires also affect human health through reduced air quality and direct injuries (Albrecht et al. 2007; Butry et al. 2001; Ebi et al. 2008). Expanding population will result in restrictions on prescribed burning, constraining deployment of a useful adaptive strategy (Stanturf and Goodrick 2012).

Forest disturbances caused by insects and pathogens are altered by climate changes due to factors such as increased tree stress, shifting phenology, and altered insect and pathogen lifecycles (Vose et al. 2012). Current knowledge provides limited insights into specific impacts on epidemics, associated tree growth and mortality, and economic loss in the Southeast, though the overall extent and virulence of some insects and pathogens have been on the rise (for example, Hemlock Woolly Adelgid in the Southern Appalachians) while recent declines in southern pine beetle (*Dendroctonus frontalis* Zimmerman) epidemics in Louisiana and East Texas have been attributed to rising temperatures (Friedenberg et al. 2007). Due to forests' vast extent and high cost, adaptation strategies are limited, except through post epidemic management responses – for example, sanitation cuts and species replacement.

The Southeast has the existing power plant capacity to produce 32% of the nation's electricity (U.S. Energy Information Administration 2011). Energy use is approximately 27% of the U.S. total, more than any other region (Ingram et al. 2012). Net energy demand is projected to increase, largely due to higher temperatures and increased use of air conditioning. This will potentially stress electricity generating capacity, distribution infrastructure, and energy costs. This is of particular concern for lower income households, the elderly, and other vulnerable communities (Ingram et al. 2012). Long periods of extreme heat could damage roadways by softening asphalt and cause deformities of railroad tracks, bridge joints, and other transportation infrastructure (FTA 2011).

Increasing temperatures will impact many facets of life in the Southeast. For each impact there could be many possible responses. Many adaptation responses are described in other chapters in this document. For examples, please see the sector chapter of interest and the Adaptation chapter.

Water Availability

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and impact the region's economy and unique ecosystems.

Water resources in the Southeast are abundant and support heavily populated urban areas, rural communities, unique ecosystems, and economies based on agriculture, energy, and tourism. The region also experiences extensive droughts, such as the 2007 drought in Atlanta, Georgia that created water conflicts among three states (Kunkel et al. 2012; Manuel 2008; Pederson et al. 2012; Seager et al. 2009). In northwestern Puerto Rico, water was rationed for more than 200,000 people during the winter and spring of 1997-1998 because of low reservoir levels (Larsen 2000). Droughts are one of the most frequent climate hazards in the Caribbean, resulting in economic losses and anxiety (Farrell et al. 2010). Water supply and demand in the Southeast are influenced by many changing factors, including climate (for example, temperature increases that contribute to increased transpiration from plants and evaporation from soils and water bodies), population, and land use (Ingram et al. 2012).

With projected increases in population, conversion of rural areas, forestlands, and wetlands into residential, commercial, industrial, and agricultural zones is expected to intensify (Loveland et al. 2012). The continued development of urbanized areas will increase water demand, exacerbate saltwater intrusion into freshwater aquifers, and threaten environmentally sensitive wetlands bordering urban areas (Heimlich et al. 2009).

Additionally, higher sea levels will accelerate saltwater intrusion into freshwater supplies from rivers, streams, and groundwater sources near the coast. Porous aquifers in some areas make them particularly vulnerable to salt water intrusion (Obeysekera et al. 2011; SFWMD 2009). For example, officials in the City of Hallandale Beach, Florida have already abandoned six of their eight drinking water wells (Berry et al. 2011).

With increasing demand for food and rising food prices, irrigated agriculture will expand in some states. Also, population expansion in the region is expected to increase domestic water demand. Such increases in water demand by the energy, agricultural, and urban sectors will increase the competition for water, particularly in situations where environmental water needs conflict with other uses (Ingram et al. 2012).

Box: Water Recycling

Because of Clayton County, Georgia's, innovative water recycling project during the 2007-2008 drought, they were able to maintain reservoirs at near capacity and an abundant supply of water while neighboring Lake Lanier, the water supply for Atlanta, was at record lows. Clayton County developed a series of constructed wetlands used to filter treated water that recharges groundwater and supplies surface reservoirs. They have also implemented efficiency and leak detection programs. (American Rivers et al. 2009).

-- end box --

Net water supply in the Southeast is expected to decline over the next several decades, particularly in the western part of the region (based on Caldwell et al. 2012). Analysis of current and future water resources in the Caribbean shows many of the small islands would be exposed to severe water stress under all climate change scenarios (UNEP 2008).

Trends in Water Availability

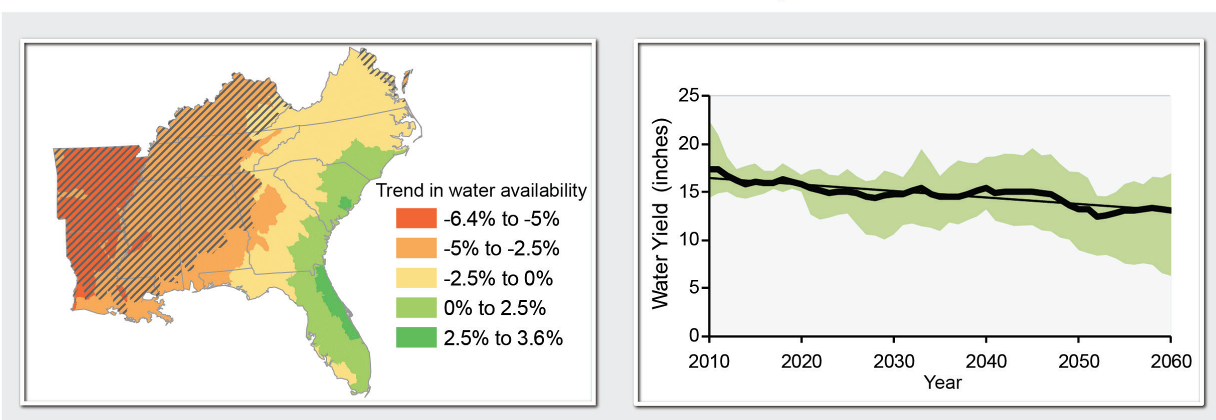


Figure 17.11: Trends in Water Availability

Caption: Left: Average annual water yield (equivalent to water availability) trends projected for 2010-2060 (based on A1B & B2 emissions scenarios) compared to the average from 2001-2010. Statistical confidence in the projected changes is highest in the hatched areas. **Right:** Projected Southeast-wide 10-year moving-average annual water yield. The green area represents the range in predicted water yield from four climate model projections based on the A1B & B2 emissions scenarios. As shown on the map, the western part of the Southeast region is expected to see the largest reductions in water availability. Figure source: based on (Caldwell et al. 2012).

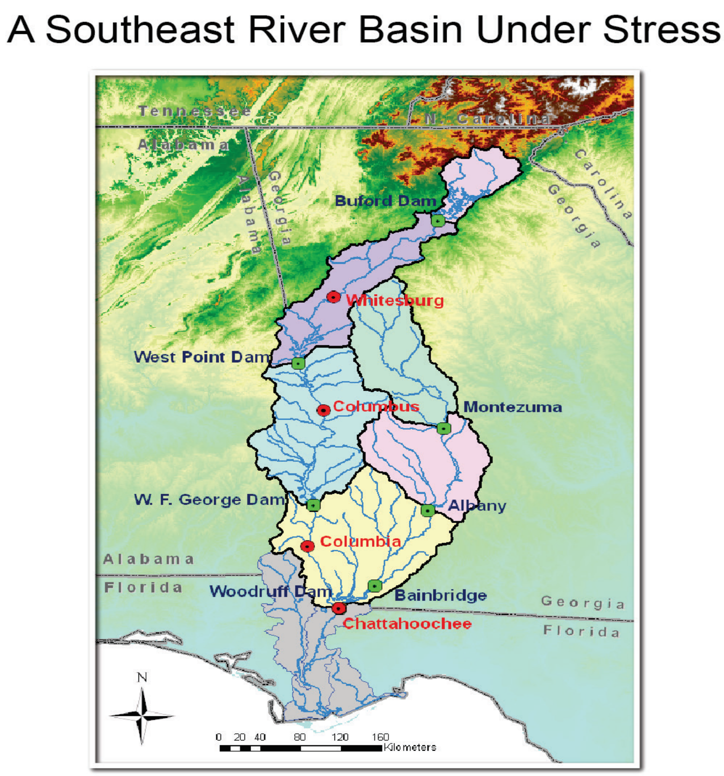


Figure 17.12: A Southeast River Basin Under Stress

Caption: The Apalachicola-Chattahoochee-Flint River Basin in Georgia exemplifies a place where many water uses are in conflict, and this conflict is expected to be exacerbated by future climate change (Georgakakos et al. 2010). The basin drains 19,600 square miles in three states and supplies water for multiple, often competing, uses, including irrigation, drinking water and other municipal uses, power plant cooling, navigation, hydropower, recreation, and ecosystems. Under future climate change, this basin is likely to experience more severe water supply shortages, more frequent emptying of reservoirs, violation of environmental flow requirements, less energy generation, and more competition for remaining water. Adaptation options include changes in reservoir storage and release procedures, and possible phased expansion of reservoir capacity (Georgakakos and Zhang 2011; Georgakakos et al. 2011; Georgakakos et al. 2010).

New freshwater well fields may have to be established inland to replenish water supply lost from existing wells closer to the ocean once they are compromised by salt water intrusion. Programs to increase water-use efficiency, reuse of waste water, and water storage capacity are options that can help alleviate water supply stress.

The Southeast, which has a disproportionate number of the fastest growing metropolitan areas in the country and important economic sectors located in low-lying coastal areas, is particularly vulnerable to some of the expected impacts of climate change. The most severe and widespread impacts are likely to be associated with sea level rise and changes in temperature and precipitation, which ultimately affect water availability. Changes in land use and land cover, more rapid in the Southeast than most other areas of the country, often interact with and serve to amplify the effects of climate change on southeastern ecosystems.

Traceable Accounts

Chapter 17: Southeast and Caribbean

Key Message Process: A central component of the process was the SE Regional Climate assessment workshop that was held on September 26-27, 2011 in Atlanta, with approximately 75 attendees, to begin the process leading to a foundational Technical Input Report (TIR). That 344-page foundational "Southeast Region Technical Report to the National Climate Assessment" (Ingram et al. 2012) comprised 14 chapters from over 100 authors, including all levels of government, NGOs, and business.

The writing team held a 2-day meeting in April, 2012 in Ft. Lauderdale, engaged in multiple technical discussions via teleconferences and webinars, which included careful review of the foundational TIR (Ingram et al. 2012)., of nearly 60 additional technical inputs provided by the public, and other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the SE chapter writing team and lead author of each key message.

Key message #1/3	**Sea level rise poses widespread and continuing threats to both natural and built environments, and the economy.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the SE Technical Input (Ingram et al. 2012). A total of 57 Technical Input Reports (TIR's) on a wide range of sea level rise topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence that the rate of sea level rise has increased is based on satellite altimetry data and direct measurements such as tide gauges. Numerous peer-reviewed publications describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation for the Southeast. For sea level rise, the authors relied on the NCA SLR scenario (Parris et al. 2012) and detailed discussion in Ingram et al. (2012). Evidence that sea level rise is a threat to natural and human environments is documented in detail within Ingram et al. (2012) and other TIR's, as well as considerable peer-reviewed literature, with examples of areas that are being flooded more regularly, salt water intrusion into fresh water wells, and changes from fresh to salt water in coastal ecosystems (e.g. fresh water marshes) causing them to die, and increases in vulnerability of many communities to coastal erosion is well documented in field studies. Economic impacts are seen in the cost to avoid flooded roads, buildings, ports, the need to drill new fresh water wells, and the loss of coastal ecosystems and their storm surge protection.
New information and remaining uncertainties	Tremendous improvement has been made since the last IPCC evaluation of sea level rise in 2007, with strong evidence of mass loss of Greenland icecap and glaciers worldwide. Improved analyses of tide gauges, coastal elevations, and circulation changes in offshore waters have also provided new information on accelerating rates of rise. These have been documented in the NCA Sea Level Change Scenario document (Parris et al. 2012). Uncertainties in the rate of sea level rise through the 21st century stems from a combination of large differences in projections between different climate models, natural climate variability, uncertainties in the melting of land based glaciers and the Antarctic and Greenland ice sheets especially, and future rates of fossil fuel emissions. A second key uncertainty is the rate of vertical land movement at specific locations. The two factors – sea level rise and subsidence, when combined, increase the impact of global sea level rise in any specific area. A third area of uncertainty is where and what adaptive plans and actions are being undertaken to avoid flooding and associated impacts in areas that affect people, communities,

	facilities, infrastructure, and ecosystems.
Assessment of confidence based on evidence	Nearly all studies to date published in the peer-reviewed literature agree that sea level rise will continue if greenhouse gas concentrations continue to rise. Because sea levels determine the locations of human activities and ecosystems along the coasts, increases in sea level and the rate of rise will nearly certainly have substantial impacts on natural and human ecosystems along the coastal area. What specific locations will be impacted under what specific levels of sea level rise need to be determined location-by-location. However, since many locations are already being impacted by rising seas, more and more locations will be impacted as the sea levels continue to rise. Confidence in this key message is therefore judged to be **very high**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #2/3	**Rising temperatures and the associated increase in frequency, intensity, and duration of extreme heat events are already and will continue to affect public health, the natural and urban environments, energy, agriculture, and forestry.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the SE Technical Input (Ingram et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe increasing hazards associated with heat events and rising temperatures for the Southeast. For temperature and associated heat events, Kunkel et al. (2012) worked closely with the region's state climatologists on both the climatology and projections. Evidence of rising temperatures and current impacts is based on an extensive set of field measurements. There is considerable evidence of high air temperature effects across a wide range of natural and managed systems in the SE. Increased temperatures affect human health and hospital admissions (Kovats and Hajat 2008; O'Neill and Ebi 2009; Portier et al. 2010; Tagaris et al. 2009). Rising water temperatures also increase risks of bacterial infection from eating Gulf Coast shellfish (Martinez-Urtaza et al. 2010) and increase algal blooms that have negative human health effects (Hallegraeff 2010; Moore et al. 2008; Tester et al. 2010; Tirado et al. 2010). There is also evidence that there will be an increase in favorable conditions for mosquitos that carry diseases (CDC 2010). Higher temperatures are detrimental to natural and urban environments, through increased wildfires in natural areas and managed forests (Delfino et al. 2009; Gramley 2005; Morton et al. 2012; Stanturf and Goodrick 2012) and invasiveness of some nonnative plants (Hellmann et al. 2008). High temperatures also contribute to more roadway damage and deformities of transportation infrastructure such as railroad tracks and bridges (FTA 2011). In addition, high temperature increases net energy demand and costs, placing more stress on electricity generating plants and distribution infrastructure. Increasing temperatures in the SE causes more stresses on crop and livestock agricultural systems. Heat stress reduces dairy and livestock production (West 2003) and also reduces yields of various crops grown in this region (corn, soybean, peanuts, rice, cotton) (Alexandrov and Hoogenboom 2000; Hatfield et al. 2008).
New information and remaining uncertainties	Since 2007, studies on impacts of higher temperatures have increased in many areas. Most of the publications cited above concluded that increasing temperatures in the SE will result in negative impacts on human health, the natural and urban environments, energy, agriculture and forestry. A key issue (uncertainty) is the detailed mechanistic responses, including adaptive capacities and/or resilience, of natural and urban environments, the public health system, energy systems, agriculture, and forests to rising temperatures and extreme heat events. Another uncertainty is how combinations of stresses, in addition to extreme heat for example, water availability, will impact the outcomes. There is a need for more monitoring to document the extent and location of vulnerable areas (natural and human), and then research to assess how those impacts will affect productivity of

	key food and forest resources and human livability as well as research that develops or identifies more resilient, adapted systems.
Assessment of confidence based on evidence	**Temperature Rise:** There is **high** confidence in documentation that projects increases in air temperatures (but not in the precise amount) and resulting changes in extreme heat events. Projections for increases in temperature are more certain in the SE than those for changes in precipitation. Rising temperatures and the substantial increase in duration of high temperatures (for either scenario) above critical thresholds will have significant impacts on the population, agricultural industries, and ecosystems in the region. There is **high** confidence in documentation that increases in temperature in the SE will result in higher risks of negative impacts in human health, agricultural and forest production, on natural systems, on the built environment, and on energy demand. There is **lower** confidence in the magnitude of these impacts, partly due to lack of information on how these systems will adapt or be adapted to higher temperatures and partly due to the limited knowledge base on the wide diversity that exists across this region in terms of climates and systems.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 17: Southeast and Caribbean

Key Message Process: See key message #1.

Key message #3/3	**Decreased water availability exacerbated by population growth and land-use change will continue to increase competition for water and impact the region's economy and unique ecosystems.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the SE Technical Input (Ingram et al. 2012). Technical Input reports (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Chapter 2, Our Changing Climate, describes evidence for drought and precipitation in its key messages, and numerous salient literature leading to decreased water availability is also summarized for the Southeast in Ingram et al. (2012) Evidence for the impacts on the region's economy and unique ecosystems is also detailed in Ingram et al. (2012) and the broader literature surveyed by the authors.
New information and remaining uncertainties	Many studies have been published since 2007 documenting increasing demands for water in the SE due to increases in populations and irrigated agriculture in addition to water shortages due to extensive droughts (Ingram et al. 2012; Kunkel et al. 2012). There is also more evidence of losses in fresh water wells near coastlines due to salt- water intrusion (Berry et al. 2011; Obeysekera et al. 2011), and continuing conflicts among states for water use, particularly during drought periods (Georgakakos et al. 2010; Ingram et al. 2012). It is a virtual certainty that population growth in the SE will continue in the future and will be accompanied by a significant change in land-use patterns, which is projected to include a larger fraction of urbanized areas, reduced agricultural areas, and reduced forest cover. With increasing population and human demand, competition for water among agriculture, urban, and environment sectors is expected to continue to increase. However, the projected population increases between the low (B1) and high (A2) emission scenarios differ significantly (33% versus 151%). Consequently the effect of climate change on urban water demand for the low emission scenario is expected to be much lower than that of the high emission scenario. Land-use change will also alter the regional hydrology significantly, and unless measures are adopted to increase water storage, availability of freshwater during dry periods will decrease, partly due to drainage and other activities. Projected increase in temperature will increase evaporation, and in areas where precipitation is projected to decrease in response to climate change, the net amount of water supply for human and environmental uses may decrease significantly. Along the coastline of the SE, accelerated intrusion of saltwater due to sea level rise will impact both freshwater well-fields and potentially freshwater intakes in rivers and streams connected to the ocean. Although sea level rise (SLR) corresponding to the high emission scenario is much higher (twice as much), even the SLR for the low emission scenario will increasingly impact water supply availability in low-lying areas of the region as they are already being impacted by sea level rise and land subsidence. Projections of specific spatial and temporal changes in precipitation in the SE remain highly uncertain and it is important to know with a reasonable confidence the sign and the magnitude of this change in various parts of the large Southeast

	region. There are no reliable projections of evapotranspiration for the SE, another major factor that determines water yield and adds to uncertainty in water availability. There are inadequate regional studies at basin scales to determine the future competition for water supply among sectors (urban, agriculture, environment). There is a need for more accurate information on future changes in drought magnitude and frequency.
Assessment of confidence based on evidence	**High** confidence in each aspect of the key message: It is virtually certain that the water demand for human consumption in the SE will increase as a result of population growth. The past evidence of impacts during droughts and the projected changes in drivers suggest that there is a **high** confidence of the above assessment of future water availability. However, without additional studies, the resilience and the adaptive capacity of the socio-economic and environmental systems are not known with confidence. Water supply is critical for sustainability of the region, particularly in view of increasing population and land-use changes. Although climate models' precipitation projections are uncertain, the combined effects of possible decreases in precipitation, increasing evaporation losses due to warming, and increasing demands for water due to higher populations, under either scenario, will have a significant impact on water availability for all sectors.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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18. Midwest

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Key messages:

1. **In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be increasingly offset by the occurrence of extreme events such as heat waves, droughts, and floods. In the long term, combined stresses associated with climate change are expected to decrease agricultural productivity, especially without significant advances in genetic and agronomic technology.**
2. **The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The region's role as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.**
3. **Increased heat wave intensity and frequency, degraded air quality, and reduced water quality will increase public health risks.**
4. **The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large, and increasingly utilized, potential to reduce emissions that cause climate change.**
5. **Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.**
6. **Climate change will exacerbate a range of risks to the Great Lakes region, including changes in the range and distribution of important commercial and recreational fish species, increased invasive species, declining beach health, and harmful blooms of algae. Declines in ice cover will continue to lengthen the commercial navigation season.**

Introduction

The Midwest has a population of over 61million people (about 20% of the national total) and generates a regional gross domestic product of over 26 trillion dollars (about 19% of the national total) (Pryor and Barthelmie 2012). The Midwest is home to expansive agricultural lands, forests in the north, the Great Lakes, substantial industrial activity, and some of America's great cities, including eight of the nation's 50 most populous cities. Each has been impacted by shifts in population, socioeconomic changes, air and water pollution, and landscape evolution, and each exhibits vulnerability to both climate variability and climate change.

In general, climate change will tend to amplify existing risks from climate to people, ecosystems, and infrastructure in the Midwest. Direct effects of increased heat stress, flooding, drought, and late spring freezes on natural and managed ecosystems may be altered by changes in pests and disease prevalence, increased competition from non-native or opportunistic native species, ecosystem disturbances, land-use change, landscape fragmentation, atmospheric pollutants, and economic shocks such as crop failures or reduced yields due to extreme weather events. These added stresses, when taken collectively, are projected to alter the ecosystem and socioeconomic patterns and processes in ways that most people in the region would consider detrimental.

Climate change may also augment or intensify other stresses on vegetation encountered in urban environments, including increased atmospheric pollution, heat island effects, salt damage, a highly variable water cycle, and frequent exposure to new pests and diseases. Much of the region's fisheries, recreation, tourism, and commerce depend on the Great Lakes and expansive northern forests, which already face pollution and invasive species pressure – pressures exacerbated by climate change. Most of the region's population lives in urban environments, with aging infrastructure, that are particularly vulnerable to climate-related flooding and life-threatening heat waves. Some cities within the region are already engaged in the process of capacity building or are actively building resilience to the threats posed by climate change. Although the region's highly energy-intensive economy emits a disproportionately large amount of gases responsible for warming the climate (also called greenhouse or heat-trapping gases), it also has a large, and increasingly realized, potential to reduce them.

The rate of warming in the Midwest has markedly accelerated over the past few decades. Between 1900 and 2010, the average Midwest air temperature increased by more than 1°F. However, between 1950 and 2010, the average temperature increased twice as quickly, and between 1980 and 2010 it increased three times as quickly (Pryor and Barthelmie 2012). Warming has been more rapid at night and during winter. These trends are consistent with the projected effects of increased concentrations of heat-trapping gases, and the spatial variability of trends is also influenced by land-use changes and increased use of irrigation (Pan et al. 2009; Pryor and Barthelmie 2012). The amount of future warming will depend on changes in the atmospheric concentration of heat-trapping gases. Projections for regionally averaged temperature increases by the middle of the century (2046-2065) relative to 1979-2000 are approximately 3.8°F for a scenario with substantial emissions reductions (B1), and 4.9°F for the current high emissions trend scenario (A2). The projections for the end of the century (2081-2100) are approximately 5.6°F for the low emission scenario, and 8.5°F for the high emission scenario (Pryor et al. in press).

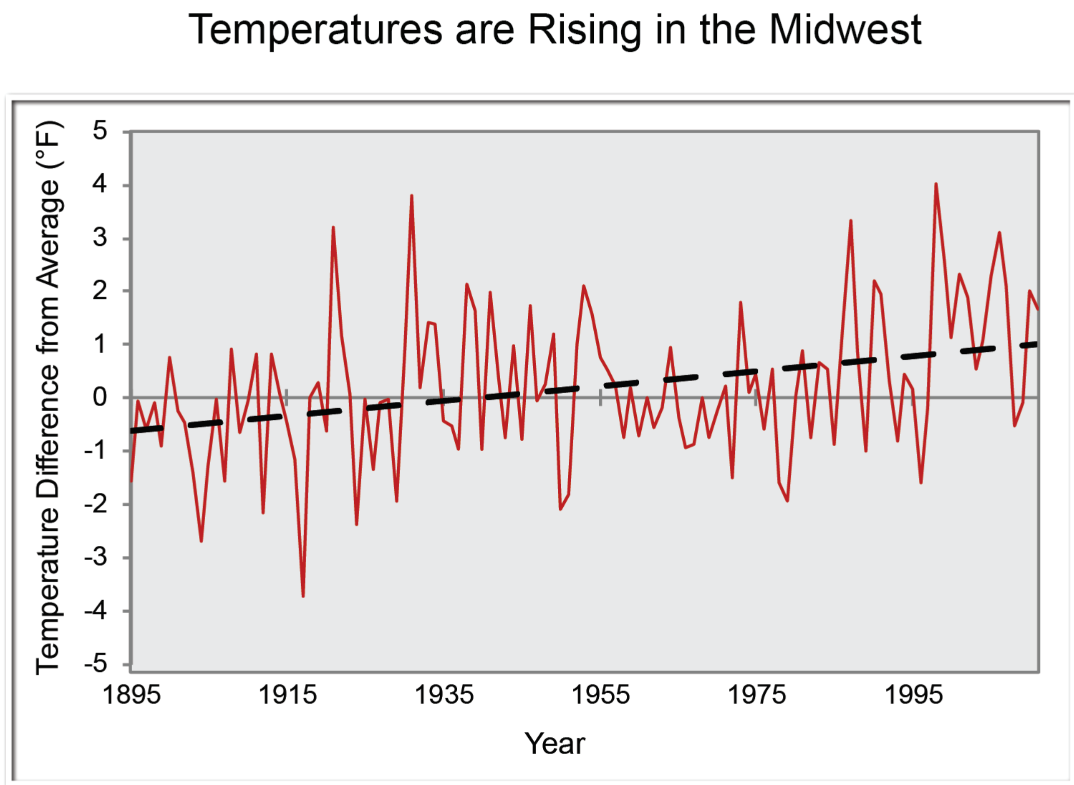

Figure 18.1: Temperatures are Rising in the Midwest

Caption: Annual average temperatures across the Midwest show a trend towards increasing temperature. The trend calculated over the period 1895-2010 is equal to an increase of 1.5°F. (Figure and data from NOAA NCDC / CICS-NC)

In 2011, 11 of the 14 U.S. weather-related disasters with damages of more than $1 billion affected the Midwest (http://www.noaa.gov/extreme2011/). Several types of extreme weather events have already increased in frequency or intensity due to climate change and further increases are projected (Rahmstorf and Coumou 2011).

Impacts to Agriculture

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be increasingly offset by the occurrence of extreme events such as heat waves, droughts, and floods. In the long-term, combined stresses associated with climate change are expected to decrease agricultural productivity, especially without significant advances in genetic and agronomic technology.

Agriculture dominates Midwest land use, with more than two-thirds of land designated as farmland (Pryor et al. in press). The region accounts for about 65% of U.S. corn and soybean production (ERS 2012), mostly from non-irrigated lands (Pryor and Barthelmie 2012). Corn and soybeans constitute 85% of Midwest crop receipts, with high value crops such as fruits and vegetables making up most of the remainder (National Agricultural Statistics Service 2012).

Corn and soybean yields increased markedly over the last century largely due to technological innovation, but are still vulnerable to year-to-year variations in weather conditions (Niyogi and Mishra 2012).

The Midwest growing season lengthened by almost two weeks since 1950, due in large part to earlier timing of the last spring freeze (Schoof 2009). This trend is expected to continue (Mearns et al. 2012; Pryor et al. in press), though the potential agricultural consequences are complex and vary by crop. For corn, small long-term average temperature increases will shorten the duration of reproductive development, leading to yield declines (Hatfield et al. 2011), even when offset by carbon dioxide (CO_2) fertilization (Leakey 2009). For soybean, yields are likely to (greater than a 2 in 3 chance) increase early in this century due to CO_2 fertilization, but these increases are projected to be offset later by higher temperature stress (Lobell and Field 2007) (see projections of an increase in number of summer days with temperatures over 95°F in the figure below).

Temperature Details Show a Range of Changes

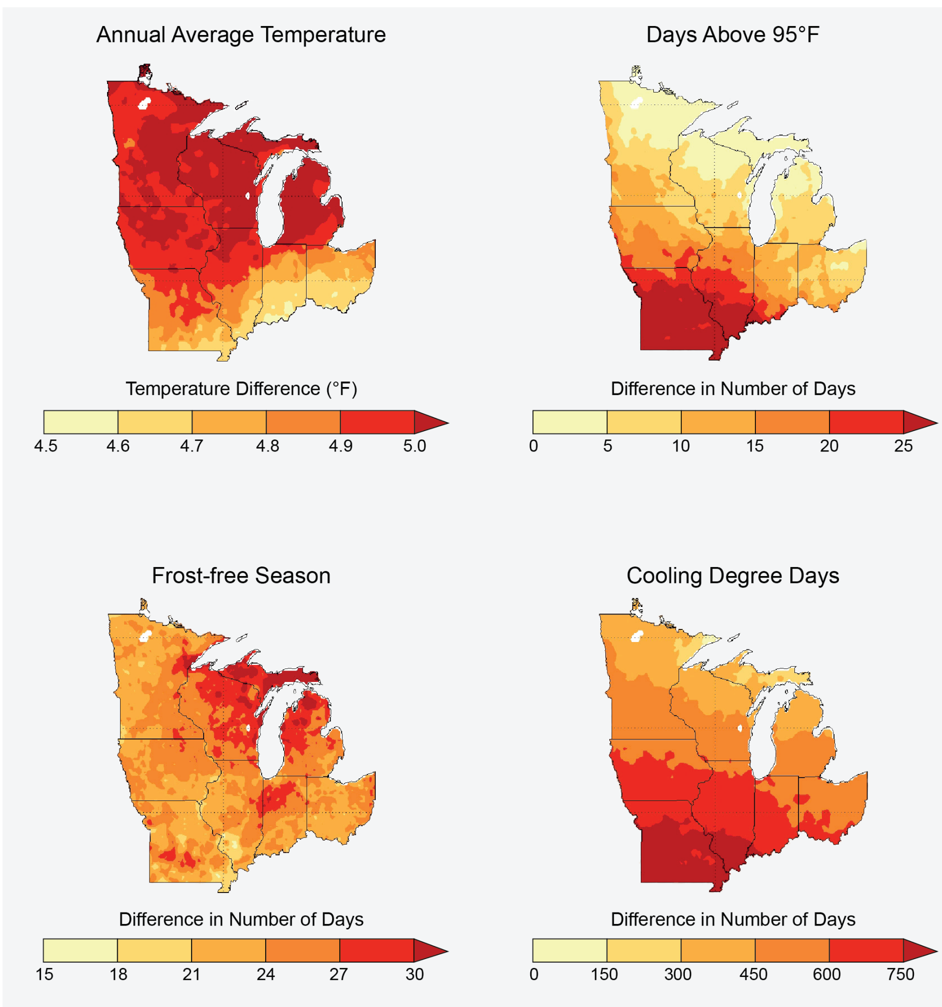

Figure 18.2: Temperature Details Show a Range of Changes

Caption: Increasing annual average temperatures (top left) by the mid-century (2041-2070) as compared to the 1971-2000 period tell only part of the climate change story. Maps also show projected increases in the number of the hottest days (days over 95°F, top right), longer growing seasons (bottom left), and an increase in cooling degree days (bottom right), which generally leads to an increase in energy use for air conditioning. Projections are from Global Climate Models that assume emissions of heat-trapping gases continue to rise (A2 scenario). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Multi-model Mean.)

Extreme weather events will influence future crop yields more than changes in average temperature or annual precipitation. High temperatures during early spring, for example, can decimate fruit crop production when early heat causes premature bud break that exposes flowers to later cold injury (Winkler et al. 2012), as happened in 2002, and again in 2012, to Michigan's $60 million tart cherry crop. Springtime cold air outbreaks are projected to continue to occur throughout this century (Vavrus et al. 2006). As a result, any increased productivity of some crops due to higher temperatures, longer growing seasons, and elevated CO_2 concentrations could be offset by increased freeze damage (Gu et al. 2008). Heat waves during pollination of field crops such as corn and soybean also reduce yields (Hatfield et al. 2011). Wetter springs may reduce crop yields and profits (Rosenzweig et al. 2002), especially if growers are forced to switch to late-planted, shorter-season varieties.

Agriculture is responsible for about 8% of U.S. heat-trapping gas emissions (U.S. Environmental Protection Agency 2012) and there is tremendous potential for farming practices to reduce emissions or store more carbon in soil (Council for Agricultural Science and Technology 2011). Although large-scale agriculture in the Midwest historically led to decreased carbon in soils, higher crop residue inputs and adoption of different soil management techniques have reversed this trend. Other techniques, such as planting cover crops and no-till soil management, can further increase CO_2 uptake and reduce energy use (Gelfand et al. 2010; Pan et al. 2012). Methane released from animals and their wastes can be reduced by altered diets and methane capture systems, and nitrous oxide production can be reduced by judicious fertilizer use (Robertson et al. 2012) and improved waste handling (Council for Agricultural Science and Technology 2011). In addition, if biofuel crops are grown sustainably (Robertson et al. 2008), they offer emission reduction opportunities by substituting for fossil fuel-based energy (Ch. 10: Water, Energy, and Land Use).

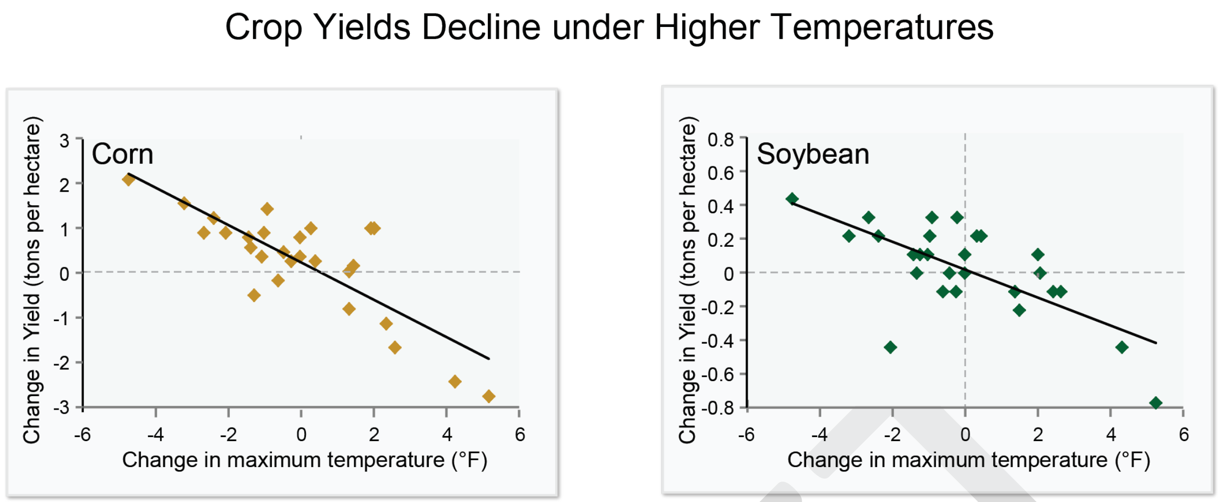

Figure 18.3: Crop Yields Decline under Higher Temperatures

Caption: Crop yields are especially sensitive to high temperatures during the pollination and grain filling period. Corn (left) and soybean (right) harvests were lower in years with higher maximum summer (June, July, August) temperatures than the average during 1980 to 2007. (Source redrawn from Mishra and Cherkauer 2010).

Forest Composition

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The region's role as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

The combined effects of climate change, land-use change, and increasing numbers of invasive species are the primary threats to Midwest natural ecosystems (Dale et al. 2011). Species most vulnerable to climate change include those that: occur in isolated habitats; live near their physiological tolerance limits; have specific habitat requirements, low reproductive rates or limited dispersal capability; are dependent on interactions with specific other species; or have low genetic variability (Brook et al. 2008; Foden et al. 2008; Parmesan 2006). Many iconic tree species such as paper birch, quaking aspen, balsam fir, and black spruce are projected to shift out of the U.S. into Canada, while many other species, such as oaks and pines, may remain in the U.S. but expand their habitat range northward (Hellmann et al. 2010; Iverson et al. 2008; Swanston et al. 2011). There is considerable variability in the likelihood of a species' habitat changing and the adaptability of the species with regard to climate change (Prasad et al. 2007). Migration to accommodate changed habitat is expected to be slow for many Midwest species, due to relatively flat topography, high latitudes, and fragmented habitats, including the Great Lakes barrier. To reach areas that are 1.8°F cooler, species in mountainous terrains need to shift 550 feet higher in altitude (which can be achieved in only a few miles), whereas species in flat terrain like the Midwest must move as much as 90 miles north to reach a similarly cooler habitat (Jump et al. 2009).

Although global forests currently capture and store more carbon each year than they emit (Pan et al. 2011), the ability of forests to act as large, global carbon absorbers ("sinks") may be reduced by projected increased disturbances from insect outbreaks (Bradley et al. 2010), forest fire (Liu et al. 2010), and drought (Allen et al. 2010), leading to increases in tree mortality and carbon emissions. Though large uncertainties exist, some regions may even shift from being a carbon sink to a source (Birdsey et al. 2006; Reich 2011). However, Midwest forests are more resilient to forest carbon losses than most Western forests because of relatively high moisture availability, greater nitrogen deposition (which tends to act as a fertilizer), and lower wildfire risk (Birdsey et al. 2006; Reich 2011; Williams et al. 2012).

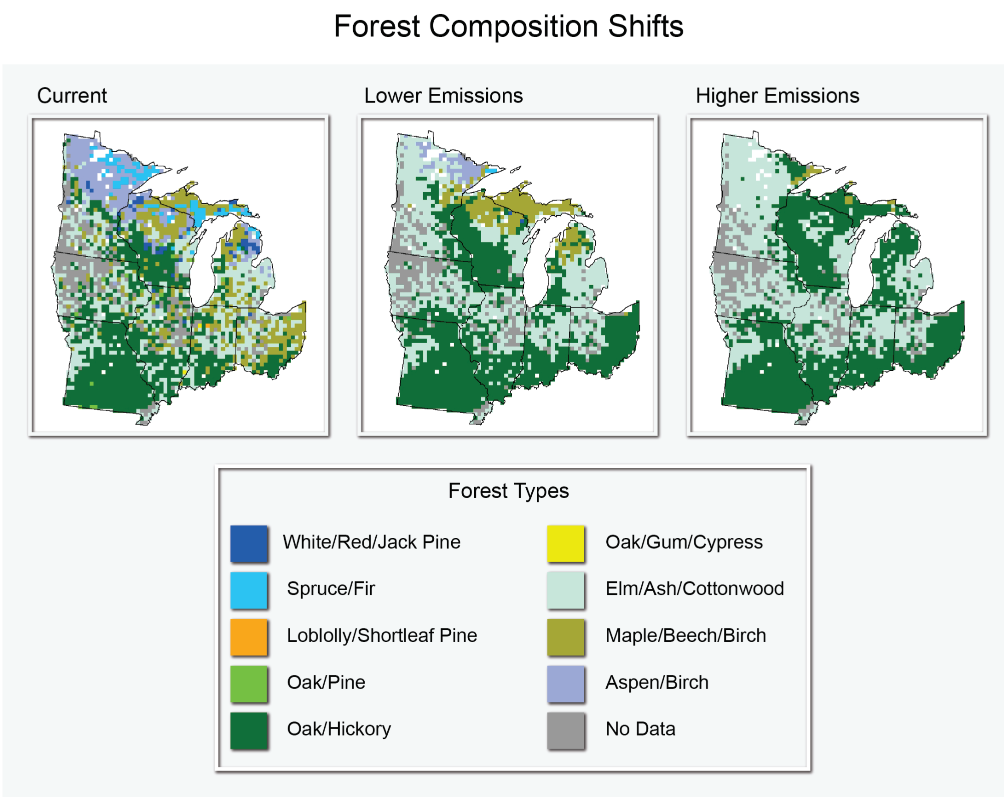

Figure 18.4: Forest Composition Shifts

Caption: As climate changes, species adapt by changing their range in response to the shifting suitable habitat. Maps show current and projected future (2100) distribution of forest types in the Midwest under two emissions scenarios, a lower scenario that assumes substantial reductions in heat-trapping gas emissions (B1), and higher scenario that assumes continued increases in emissions (A2). Maple/beech/birch, spruce/fir, and aspen/birch forests are projected to disappear from the North Woods, especially under higher emissions scenarios, while various oak forest types are projected to expand (Source: Prasad et al. 2007)

Public Health Risks

Increased heat wave intensity and frequency, degraded air quality, and reduced water quality will increase public health risks.

The Midwest has experienced major heat waves and their frequency has increased over the last six decades (Perera et al. 2012). For the U.S., mortality increases 4% during heat waves compared with non-heat wave days (Anderson and Bell 2011). During July 2011, 132 million people across the U.S. were under a heat alert – and on July 20 the majority of the Midwest experienced temperatures in excess of 100°F. Heat stress is projected to increase as a result of both increased summer temperatures and humidity (Schoof 2012). One study projected an increase of between 166 and 2,217 excess deaths per year from heat wave-related mortality in Chicago alone by 2081-2100, depending on the climate model (Peng et al. 2011). Heat response plans and early warning systems save lives, and from 1975-2004 mortality rates per heat event have declined (Sheridan et al. 2009), however, many municipalities lack such plans (Weisskopf et al. 2002).

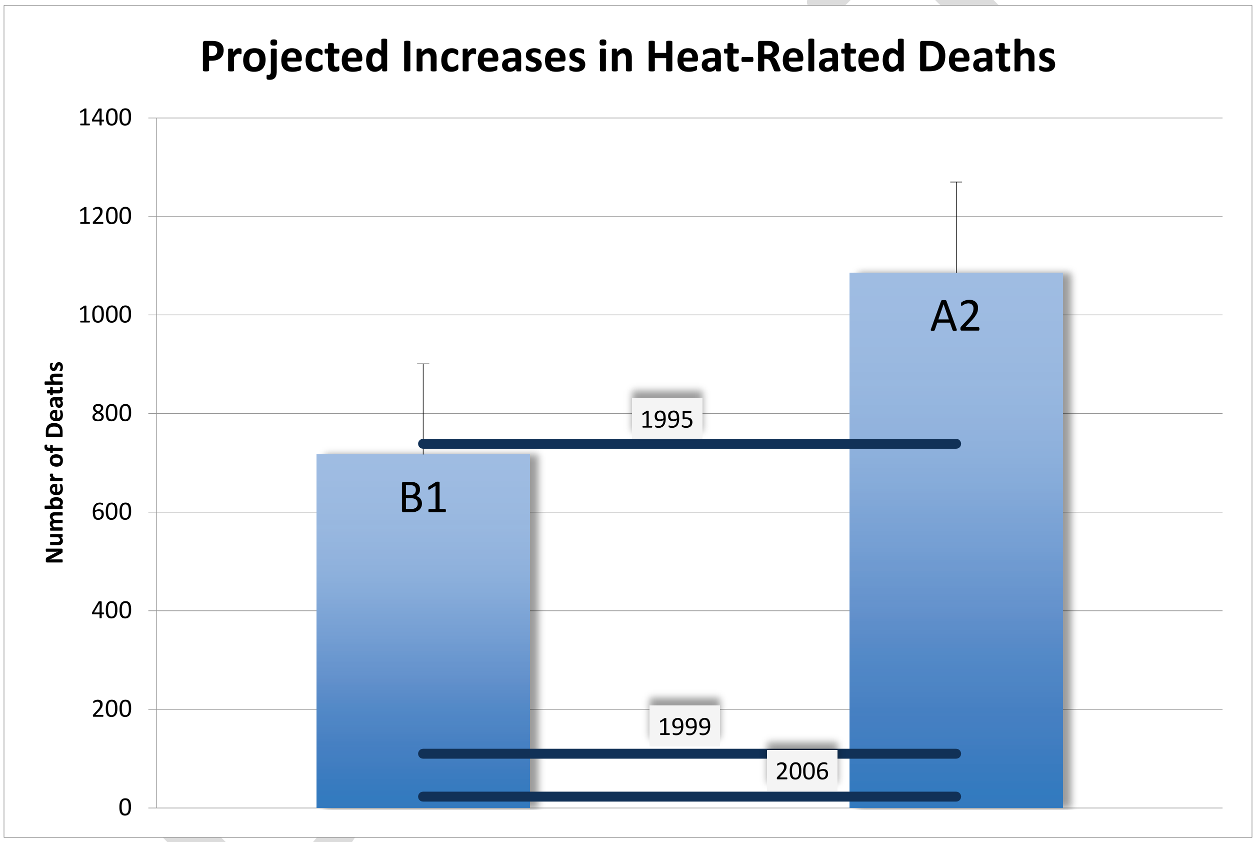

Figure 18.5: Projected Increases in Heat-Related Deaths

Caption: Chart shows observed heat-related deaths in Chicago during the 1995, 1999, and 2006 heat waves, and average projected increases in heat-related deaths for Chicago in 2081-2100 from 7 different climate models, assuming significant reductions in emissions of the gases that cause global warming (left bar) and if emissions continue to increase (right bar). (Source: Peng et al. 2011). Differences in the duration, intensity and spatial extent of the historical heat-waves (Palecki et al. 2001) explain some of the differences in the number of deaths caused as does increased mitigation efforts.

More than 20 million people within the Midwest currently experience air quality that fails to meet national ambient air quality standards (Pryor and Barthelmie 2012). This exposure to degraded air quality due to human-induced emissions (Holloway et al. 2008) and increased pollen season duration (Ziska et al. 2011) is projected to be amplified under higher temperatures (Jacob and Winner 2009), and thus increase the human health effects from heat waves. However, policy options exist that could reduce emissions of both heat-trapping gases and other air pollutants, yielding benefits for human health and fitness. Increased temperatures could also increase the vulnerability of the Midwestern population to diseases carried by insects and rodents (Ashley and Meentemeyer 2004; Ogden et al. 2004; Ward et al. 2004).

Box 1: Alternative Transportation Options Create Multiple Benefits

The transportation sector produces one-third of U.S. greenhouse gas emissions, and automobile exhaust also contains precursors to fine particulate matter (PM2.5) and ground-level ozone (O_3), which pose threats to public health. Adopting a low carbon transportation system with fewer automobiles, therefore, could have immediate health "co-benefits" of both reducing climate change and improving human health via both improved air quality and physical fitness. The maps below projects health benefits if automobile trips shorter than 5 miles round-trip were removed for the 11 largest metropolitan areas in the Midwest: saving 1,295 lives and $8 billion in health care costs per year for the upper Midwest region alone (assumes 50% of the short trips are by bicycle, saves $5 billion otherwise) Grabow et al. (2012).

Reducing Emissions, Improving Health

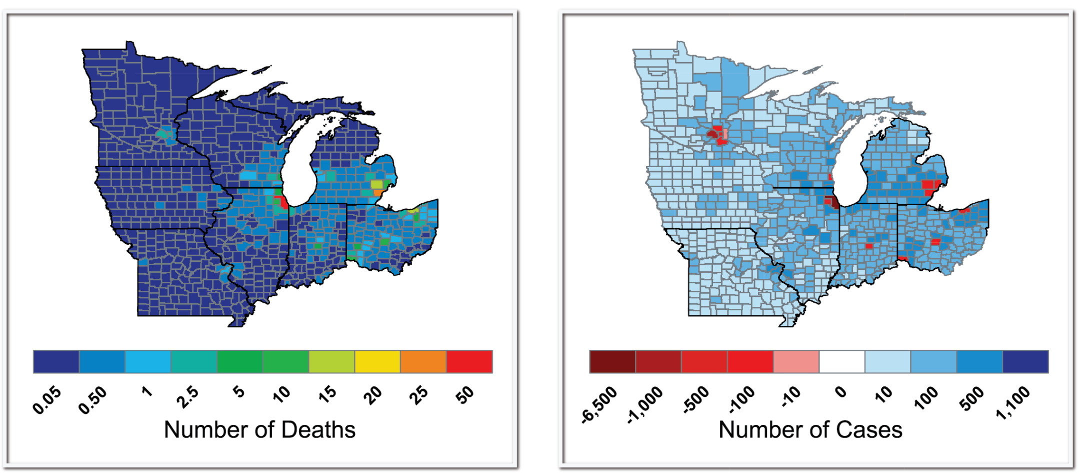

Figure 18.6: Reducing Emissions, Improving Health

Caption: Annual reduction in the number of premature deaths (left) and annual reduction in the number of acute respiratory symptoms (right) due to reductions in particulate matter and ozone caused by reducing automobile exhaust. In both maps, positive values indicate a reduction in deaths or cases, negative value on right graph indicates an increase in cases of acute respiratory symptoms (Source: Grabow et al. 2012)

-- end box --

Energy-Intensive Economy

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large, and increasingly utilized, potential to reduce emissions that cause climate change.

The Midwest is a major exporter of electricity to other U.S. regions, and has a highly energy-intensive economy. Energy use per dollar of GDP is approximately 20% above the national average, and per capita greenhouse gas emissions are 22% higher than the national average (Pryor and Barthelmie 2012). The range in seasonal air temperature makes energy demand for both heating and cooling comparatively high, with the highest demand for winter heating. The demand for heating in major Midwestern cities is typically five- to seven- times that for cooling (Pryor and Barthelmie 2012), although this is expected to shift as a result of longer summers, more frequent heat waves, and higher humidity, leading to an increase in the number of cooling degree days. This increased demand for cooling by the middle of this century is projected to exceed 10 gigawatts (equivalent to at least five large conventional power plants), requiring more than $6 billion in infrastructure investments (Gotham et al. 2012). Further, approximately 95% of the electrical generating infrastructure in the Midwest is susceptible to decreased efficiency under higher temperatures (Gotham et al. 2012).

A 2009 National Academy of Sciences study concluded that burning fossil fuels leads to damages of more than $120 billion a year due primarily to increased health care costs (see "Alternative Transportation Options Create Multiple Benefits" above) (NRC 2010). Addressing these issues and climate change presents the Midwest's energy sector with a number of challenges, in part because of its current reliance on coal-based electricity (Pryor and Barthelmie 2012) and an aging, less reliable grid (Amin 2012) that will require significant reinvestment even without additional adaptations to climate change (Midwest Independent Transmission System Operator 2011).

Compared to other regions, the Midwest has huge potential to produce energy from zero- and low-carbon sources, given its vast wind, solar, and biomass resources. More than one-quarter of national installed wind energy capacity, one-third of biodiesel capacity, and over two-thirds of ethanol production is within the Midwest (Pryor and Barthelmie 2012) (See also Ch. 4: Energy Supply and Use, and Ch. 10: Water, Energy, and Land Use). Progress is hampered by prices that are distorted through a mix of direct and indirect subsidies and unaccounted-for costs (Sovacool 2009). The region also has potential for capturing and storing (or beneficially reusing) CO_2 produced when using the region's fossil resources (coal, oil, and gas).

Increased Rainfall and Flooding

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Precipitation in the Midwest is greatest in the east, declining towards the west. Precipitation occurs about once every seven days in the western part of the region and once every three days in the southeastern part (Pryor et al. 2009a), with up to 40% of annual precipitation being concentrated into only 10 days (Pryor et al. 2009a). Generally, annual precipitation increased during the past century (by up to 20% in some locations), with much of the increase driven by intensification of the heaviest rainfalls (Pryor et al. 2009a; Pryor et al. 2009b; Villarini et al. 2011). This tendency towards more intense precipitation events is projected to continue in the future (Schoof et al. 2010).

Model projections for precipitation changes are less certain than those for temperature (Kunkel et al. 2012). Projections of average annual precipitation by late this century under a high emissions scenario (A2) range from little change to greater than 10% increases in the north, and from greater than 10% decreases to greater than 10% increases in the south (Kunkel et al. 2012; Ch. 2: Our Changing Climate; Key Message 5).

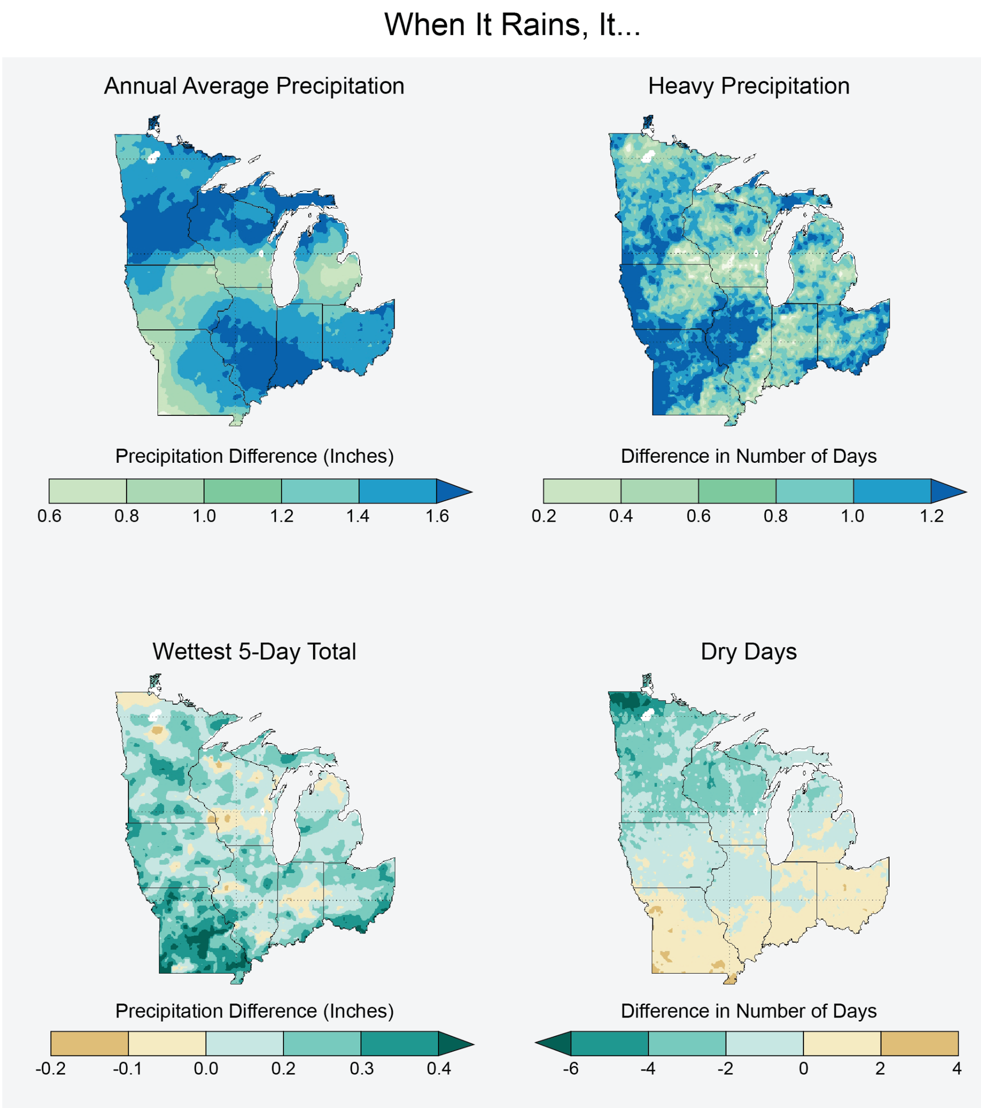

Figure 18.7: When it rains, it…

Caption: Precipitation patterns affect many aspects of life, from agriculture to urban storm drains. These maps show projected changes based on Global Climate Model output for the middle of the current century (2041-2070) relative to the end of the last century (1971-2000) across the Midwest. **Top left:** the changes in total annual average precipitation. Across the entire Midwest, the total amount of water from rainfall and snowfall is projected to increase. **Top right:** increase in the number of days with very heavy precipitation (top 2% of all rainfalls). **Bottom left:** shows increases in the amount of rain falling in the wettest 5-day period. Both indicate that heavy precipitation events will increase in intensity in the future across the Midwest. **Bottom right:** change in the average number of days with less than one-tenth of an inch of precipitation. An increase in this variable has been used to indicate an increase in the chance of drought in the future. (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Multi-model Mean.)

Flooding carries major human and economic consequences through inundating urban and agricultural land, but also by disrupting navigation in the region's roads, rivers, and reservoirs. For example, the 2008 flooding in the Midwest caused 24 deaths, $15 billion of losses via reduced agricultural yields, and closure of key transportation routes (Pryor and Barthelmie 2012). Water infrastructure for flood control, navigation, and other purposes is susceptible to climate change and other forces because the designs are based upon historical patterns of precipitation and streamflow that no longer hold.

Snowfall varies across the region, comprising less than 10% of total precipitation in the south, to more than half in the north, with as much as 2 inches of water available in the snow pack at the beginning of spring melt in the northern reaches (Baun 2005). When this amount of snowmelt is combined with heavy rainfall, the resulting flooding can be widespread and catastrophic (see "Cedar Rapids" below). While recent history indicates that these types of events are becoming more frequent, and perhaps more severe, both observed records and climate models project less snow in the southern portions of the region and greater lake effect snow, making overall regional impacts difficult to assess. Large-scale flooding can also occur due to extreme precipitation in the absence of snowmelt (for example, Rush Creek and the Root River, MN in August 2007 and multiple rivers in southern Minnesota in September 2010) (Ellison et al. 2011). These warm season events are projected to increase in magnitude. Such events tend to be more regional and less likely to cover as large an area, in part because soil water storage capacity is typically much greater during the summer.

Box: Cedar Rapids: Tale of Vulnerability and Response

Cedar Rapids, Des Moines, Iowa City, and Ames, Iowa have all suffered multi-million-dollar losses from floods since 1993. In June 2008, a record flood event exceeded the once-in-500-year flood level by more than 5 feet, causing $5 to $6 billion in damages from flooding, or more than $40,000 per resident of the city of Cedar Rapids (Budikova et al. 2010). The flood inundated much of the downtown, damaging more than 4,000 structures, including 80% of governmental offices, and displacing 25,000 people (Mutel 2010). The record flood at Cedar Rapids was the result of low reservoir capacity and extreme rainfall falling on soil already saturated from unusually wet conditions. Rainfalls were similar to what occurred in 1993 (8 inches over a two week period) that overwhelmed a flood control system designed largely for a once-in-100-yr flood event. Such events are consistent with observations and projections of most models indicating wetter springs and more intense precipitation events. With the help of more than $3 billion in funding from the federal and state government, Cedar Rapids is recovering and has taken significant steps to reduce future flood damage, with buyouts of more than 1,000 properties, and numerous buildings adopting flood protection measures.

-- end box --

Changing land use and the expansion of urban areas are reducing infiltration of water into the soil and increasing surface runoff. These changes exacerbate impacts caused by increased precipitation intensity. Many major Midwest cities are served by combined storm and sewage drainage systems. As impervious surfaces (such as asphalt) increase and extreme precipitation events intensify, combined sewer overflow has degraded water quality (Patz et al. 2008). The EPA estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually (McLellan et al. 2007). The Great Lakes provide drinking water to more than 40 million people and are home to more than 500 beaches (Patz et al. 2008), and have been subject to recent sewage overflows. For example, stormwater across the city of Milwaukee recently showed high human fecal pathogen levels at all 45 outflow locations, signifying widespread sewage contamination (Sauer et al. 2011). One study estimated that increased storm events will lead to an increase of up to 120% in combined sewer overflows into Lake Michigan by 2100 under a scenario of very high emissions (A1F1)(Patz et al. 2008), leading to additional human health issues and beach closures. Municipalities may be forced to invest in new infrastructure to protect human health and the lakes, and local communities could face tourism losses from fouled near-shore regions.

Increased precipitation intensity also increases erosion, damaging ecosystems and increasing delivery of sediment and subsequent loss of reservoir storage capacity. Increased storm-induced agricultural runoff and rising water temperatures have increased non-point source pollution problems in recent years (Mishra et al. 2010). This has led to increased phosphorus and nitrogen loadings contributing to more and prolonged occurrences of low-oxygen "dead zones" and to harmful, lengthy, and dense algae growth within the Great Lakes and other Midwestern water bodies (Reutter et al. 2011). (Such zones and their causes are also discussed in Ch. 25: Coastal Zone, Ch. 18: Biogeochemical Cycles, and Ch. 3: Water Resources, which has a key message on water quality). Watershed planning can be used to alleviate water quantity and quality problems due to changing climate and land use.

While there was no apparent change in drought duration in the Midwest over the past century (Dai 2010), the average number of days without precipitation is projected to increase in the future. This could lead to agricultural drought and suppressed crop yields (Niyogi and Mishra 2012) (See also Ch. 4: Energy Supply and Use, and Ch. 10: Water, Energy, and Land Use). This would increase thermoelectric power plant cooling water temperatures and decrease cooling efficiency and plant capacity because of the a need to avoid discharging excessively warm water (Gotham et al. 2012).

Increased Risks to the Great Lakes

Climate change will exacerbate a range of risks to the Great Lakes region, including changes in the range and distribution of important commercial and recreational fish species, increased invasive species, declining beach health, and harmful blooms of algae. Declines in ice cover will continue to lengthen the commercial navigation season.

The Great Lakes, North America's largest freshwater feature, have recently recorded higher water temperatures and less ice cover as a result of changes in regional climate. Summer surface water temperatures in Lakes Huron and Ontario increased 5.2°F and 2.7°F, respectively, between 1968 and 2002 (Dobiesz and Lester 2009), with smaller increases in Lake Erie (Dobiesz and

Lester 2009; Lofgren and Gronewold 2012). Due to the reduction in ice cover, the temperature of surface waters in Lake Superior during the summer increased 4.5°F, twice the rate of increase in air temperature (Austin and Colman 2007). By 2050 and 2100, these surface temperatures are projected to rise by as much as 7.0°F and 12.1°F, respectively (Mackey 2012; Trumpickas et al. 2009). Higher temperatures, increases in precipitation, and lengthened growing seasons favor production of blue-green and toxic algae that can harm fish, water quality, habitat, aesthetics (Ficke et al. 2007; Mackey 2012; Reutter et al. 2011), and potentially heighten the impact of invasive species already present (Bronte et al. 2003; Rahel et al. 2008).

Increased winter air temperatures led to decreased Great Lakes ice cover by 71% between 1973 and 2010. Less ice, coupled with more frequent and intense storms (as indicated by some analyses of historical wind speeds, (Pryor et al. 2009c), leaves shores vulnerable to erosion and flooding and could harm property and fish habitat (Ferris 2009; Mackey 2012; Wuebbles et al. 2010). However, reduced ice cover also has the potential to lengthen the shipping season (Millerd 2011). The navigation season has increased by an average of 8 days since 1994, and the Welland Canal in the St. Lawrence River remained open nearly two weeks longer. Increased shipping days benefit commerce but could also increase shoreline scouring and bring in more invasive species (Hellmann et al. 2008; Millerd 2011; Smith et al. 2012).

Ice Cover in the Great Lakes is Declining

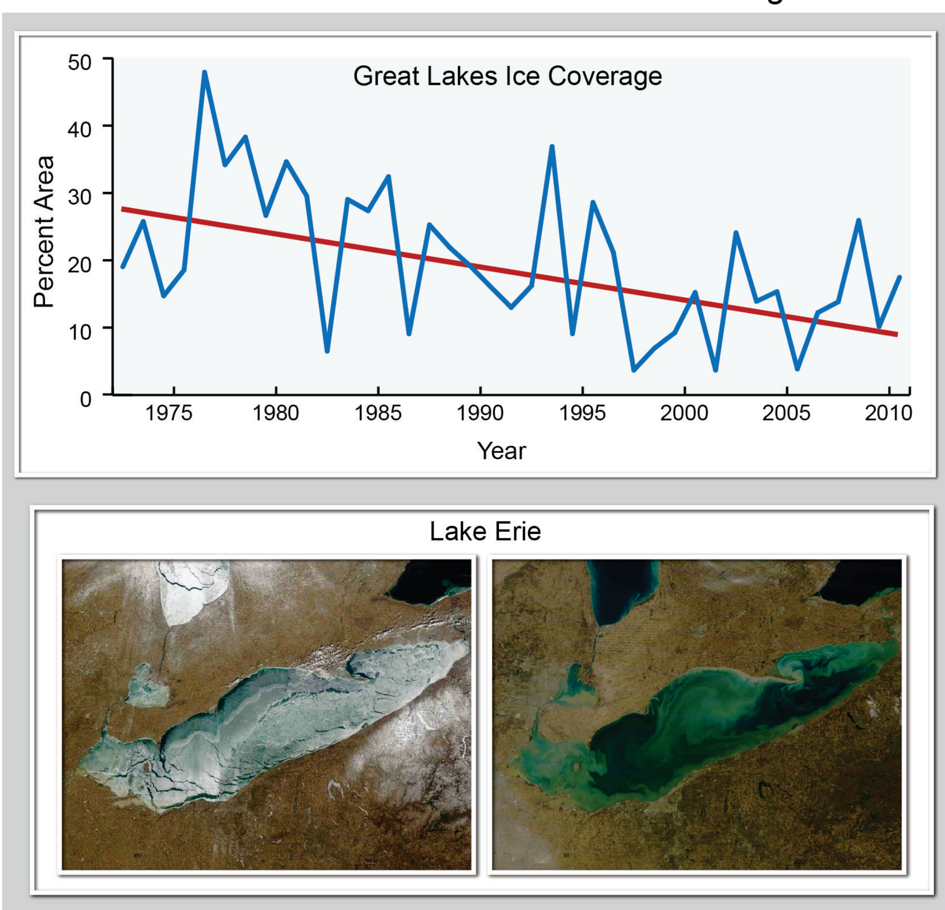

Figure 18.8: Ice Cover in the Great Lakes is Declining

Caption: From the 1970s to the present, the average annual percentage of the Great Lakes covered with ice has declined (Upper Panel). Winter of 2008-2009 (lower left) was characterized by near-normal air temperatures over the Great Lakes, while 2011-2012 (lower right) was characterized by air temperature of approximately 5.4°F (3°C) warmer than the historical average. Photos contrast extensive vs. minimal ice cover on Lake Erie. (Source: Wang et al. 2012. Images are from NASA MODIS satellite imagery processed by SSEC, University of Wisconsin and obtained from the CoastWatch Great Lakes Program).

Changes in lake levels can also influence the amount of cargo that can be carried. On average, a 1000-foot ship sinks into the water by one inch per 270 tons of cargo (Sousounis and Bisanz 2000); thus if a ship is currently draft-limited, any lowering of lake levels will result in a proportional reduction in the amount of cargo that ships can transport to the Great Lakes ports. However, current estimates of lake level changes are uncertain, even for continued increases in global greenhouse gas emissions (A2 scenario). New model projections indicate only a slight decrease or even a small rise in levels (Angel and Kunkel 2010), in contrast to earlier models (Hayhoe et al. 2010) that projected much lower levels because they overstressed water loss due to evapotranspiration from the land within the Great Lakes drainage basin (Lofgren et al. 2011; Milly and Dunne 2011; UGLSB 2012).

Traceable Accounts

Chapter 18: Midwest

Key Message Process: The assessment process for the Midwest Region began with a workshop was that was held July 25, 2011 in Ann Arbor, MI with 10 participants discussing the scope and authors for a foundational Technical Input Report (TIR) report entitled "Midwest Technical Input Report" (Winkler et al. 2012). The report, which consisted of nearly 240 pages of text organized into 13 chapters, was assembled by 23 authors representing governmental agencies, NGOs, tribes, and other entities.

The chapter author team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR (Winkler et al. 2012) and of approximately 45 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team convened teleconferences and exchange extensive emails to define the scope of the chapter for their expert deliberation of input materials, and to generate the chapter text and figures. Each expert drafted key messages, initial text and figure drafts and traceable account forms that pertained to their individual fields of excellence. These materials were then extensively discussed by the Author team and were approved by the Chapter team members.

Key message #1/6	**In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be increasingly offset by the occurrence of extreme events such as heat waves, droughts, and floods. In the long-term, combined stresses associated with climate change are expected to decrease agricultural productivity especially without significant advances in genetic and agronomic technology.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Winkler et al. 2012). Technical Input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for altered growing seasons across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 4) and its Traceable Accounts. Specific details for the Midwest are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012) with its references. Evidence for longer growing seasons in the Midwest is based on regional temperature records and incontrovertible, as is evidence for increasing carbon dioxide concentrations. USDA data tables provide evidence for the importance of the 8 Midwest states for US agricultural production. Evidence for the effect of future elevated carbon dioxide concentrations on crop yields is based on scores of greenhouse and field experiments that show a strong fertilization response for C3 plants such as soybeans and wheat and a positive but not as strong a response for C4 plants such as corn. The negative effects of extreme weather events on crop yield are based on observational data, evidence from field experiments, and quantitative modeling: early spring heat waves followed by normal frost events has been shown to decimate Midwest fruit crops; heat waves during flowering, pollination, and grain filling has been shown to significantly reduce corn and wheat yields; more variable and intense spring rainfall has delayed spring planting in some years and can be expected to increase erosion and runoff; and floods have led to crop losses.
New information and remaining uncertainties	Key issues (uncertainties) are a) the rate at which grain yield improvements will continue to occur, which could help to offset the overall negative effect of extreme events at least for grain crops (though not for individual farmers), and b) the degree to which genetic improvements could make some future crops more tolerant of extreme events such as drought and heat stress. Additional uncertainties are c) the degree to which accelerated soil carbon loss will occur as a result of warmer

	winters and the resulting effects on soil fertility and soil water availability, and d) the potential for increased pest and disease pressure as southern pests such as soybean rust move northward and existing pests better survive milder Midwest winters.
Assessment of confidence based on evidence	Since nearly all studies published to date in the peer-reviewed literature agree that Midwest crops benefit from CO_2 fertilization and some benefit from a longer growing season, there is **very high** confidence in this component of the key message. Studies also agree that full benefits will be offset partly or fully by more frequent heat waves, early spring thaws followed by freezing temperatures, more variable and intense rainfall events, and floods. Again, **very high** confidence in this aspect. There is less certainty (**high**) about pest effects and about the potential for genetic improvements to significantly mitigate the risk of crop loss.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 18: Midwest

Key Message Process: See Key Message #1.

Key Message #2/6	The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The region's role as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change
Description of evidence	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Winkler et al. 2012). Technical Input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for increased temperatures and altered growing seasons across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Messages 3 and 4) and its Traceable Accounts. Specific details for the Midwest are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012) with its references. Evidence that species have been shifting northward or ascending in altitude has been mounting for numerous species, though less so for long-lived trees. Nearly all studies to date published in the peer-reviewed literature agree that many of the boreal species of the north will eventually retreat northward. The question is when. Multiple models and paleoecological evidence show these trends have occurred in the past and are very likely to continue in the future. The forests of the Eastern United States (including the Midwest) have been accumulating large quantities of carbon over the past century, but evidence shows this trend is slowing in recent decades. There is a large amount of forest inventory data supporting the gradual decline in carbon accumulation throughout the East, as well as increasing disturbances/disturbance agents that are reducing overall net productivity in many of the forests.
New information and remaining uncertainties	A key issue (uncertainty) is the rate of change of habitats and for organisms adapting or moving as habitats move. Key questions are: How much will the habitats change (what scenarios and model predictions will be most correct)? As primary habitats move north, which species will be able to keep up with changing habitats on their own or with human intervention through assisted migration, management of migration corridors, or construction or maintenance of refugia within their current landscapes? Viable avenues to improving the information base are determining which climate models exhibit the best ability to reproduce the historical and potential future change in habitats, and determining how, how fast, and how far various species can move or adapt.
Assessment of confidence based on evidence	There is **very high** confidence in this key message.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 18: Midwest

Key Message Process: See Key Message #1.

Key Message #3/6	**Increased heat wave intensity and frequency, degraded air quality, and reduced water quality will increase public health risks**
Description of evidence	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Winkler et al. 2012). Technical Input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for extreme weather such as heat waves across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 7) and its Traceable Accounts. Specific details for the Midwest are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012) with its references. Pryor (2012) also contains chapters detailing the most current evidence for the region. Heat waves: The occurrence of heat waves in the recent past has been well-documented (Pryor and Barthelmie 2012; Schoof 2012; Winkler et al. 2012), as have health outcomes (particularly with regards to mortality). Projections of thermal regimes indicate increased frequency of periods with high air temperatures (and high apparent temperatures). These projections are relatively robust and consistent between studies. Air quality: In the region containing North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana and Ohio in 2008 over 26 million people lived in counties that failed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ and over 24 million lived in counties that failed the NAAQS for O_3. Since not all counties have air quality measurement stations in place, these data must be considered a lower bound on the actual number of counties that violate the NAAQS. Further given that the NAAQS were designed principally with the goal of protecting human health failure of these standards implies a significant fraction of the population live in counties characterized by air quality that is harmful to human health. While only relatively few studies have sought to make detailed air quality projections for the future, those that have generally indicate declining air quality (see caveats below). Water quality: The EPA estimates that roughly 3.2 trillion liters of combined sewer overflow (CSO) wastewater is discharged annually into our nation's surface waters. Sewer overflows leading to discharge of untreated as a result of unanticipated precipitation events represent a major threat to human health. While not all urban areas within the Midwest have combined sewers (designed to capture both sanitary sewage and storm-water) for delivery to wastewater treatment plants, many are (e.g. Chicago and Milwaukee), and such systems are vulnerable to CSO during extreme precipitation events. Presuming that these historical tendencies towards intensification of extreme precipitation events does not reverse into the future (and the majority of studies imply only intensification of extreme events) it appears that sewer overflow will continue to constitute a significant current health threat and a critical source of climate change vulnerability for major urban areas within the Midwest.
New information and remaining uncertainties	Key issues (uncertainties) are: Human health outcomes are contingent on a large number of non-climate variables. For example, morbidity and mortality outcomes of extreme heat are strongly determined by i) housing stock and access to air-conditioning in residences, ii)

	existence and efficacy of heat wave warning and response plans (for example, foreign language-appropriate communications and transit plans to public cooling centers, especially for the elderly), iii) co-stressors (for example, air pollution). Further heat-stress is dictated by apparent temperature (which is a function of both air temperature and humidity). Urban heat islands tend to exacerbate elevated temperatures and are largely determined by urban land-use and anthropogenic heat emissions. Urban heat island reduction plans (for example, planted green roofs) represent one ongoing intervention. Nevertheless, the occurrence of extreme heat indices will increase under all climate scenarios, thus in the absence of policies to reduce heat-related illness/death, these impacts will increase in the future. Air quality is a complex function not only of physical meteorology but emissions of air pollutants and precursor species. However, since most chemical reactions are enhanced by warmer temperatures, as are many air pollutant emissions, warmer temperatures will lead to worsening of air quality. Combined Sewage Outflow is a major threat to water quality in some Midwestern cities now. The tendency towards increased magnitude of extreme rain events (documented in the historical record and projected to continue in downscaling analyses) will cause an increased risk of waterborne disease outbreaks in the absence of infrastructure overhaul. However, mitigation actions are available, and the changing structure of cities (for example, reducing impervious surfaces) may offset the impact of the changing climate.
Assessment of confidence based on evidence	In the absence of concerted efforts to reduce the threats posed by extreme heat, degraded air quality and degraded water quality, climate change will increase the health risks associated with these phenomena. However, these projections are contingent on underlying assumptions regarding socio-economic conditions and demographic trends in the region. Confidence is therefore **high** regarding this key message.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 18: Midwest

Key Message Process: See Key Message #1.

Key Message #4/6	**The Midwest has a highly energy-intensive economy with per capita emissions of heat-trapping gases more than 20% higher than the national average. The region also has a large, and increasingly utilized, potential to reduce emissions that cause climate change.**
Description of evidence	The Midwest's disproportionately large reliance on coal for electricity generation and the energy intensity of its agricultural and manufacturing sectors are all well documented in both government and industry records, as is its contribution to greenhouse gases. The region's potential for zero- and lower-carbon energy production is also well documented by government and private assessments. Official and regular reporting by state agencies and non-governmental organizations demonstrates the Midwest's progress toward a decarbonized energy mix. The evidence is also very strong that the Midwest is steady decarbonizing its electricity generation through a combination of new state-level policies (e.g., energy efficiency and renewable energy standards) and will continue to do so in response low natural gas prices, falling prices for renewable electricity (e.g., wind and solar), greater market demand for lower-carbon energy from consumers and new EPA regulations governing new power plants.
New information and remaining uncertainties	Four key issues (uncertainties) are: 1) the net effect of emerging EPA regulations on the future energy mix of the Midwest. Assessments to date suggest a significant number of coal plants will be closed or repowered with lower-carbon natural gas; and even for coal plants that are currently thought of as "must run" (to maintain the electric grid's reliability) may be able to be replaced in some circumstances with the right combination of energy efficiency, new transmission lines, demand response and distributed generation. 2) A second key uncertainty is whether or not natural gas prices will remain at their historically low levels. Since there are really only five options for meeting electricity demand—energy efficiency, renewables, coal, nuclear and natural gas—the replacement of coal with natural gas for electricity production will have a significant impact on greenhouse gas emissions in the region. 3) A third key issue is the uncertain future for federal policies that have spurred renewable energy development to date, such as the Production Tax Credit for wind. While prices for both wind and solar continue to fall, the potential loss of tax credits may dampen additional market penetration of these technologies. 4) A fourth and final uncertainty is the net effect of climate change on energy demand, and the cost of meeting that new demand profile. Research to date suggests the potential for a significant swing from the historically larger demand for heating in the winter to more demand in the summer instead due to warmer, more humid climate.
Assessment of confidence based on evidence	There is no dispute about the energy intensity of the Midwestern economy, nor its disproportionately large contribution of greenhouse gas emissions. Similarly, there is broad agreement about the Midwest's potential for—and progress toward—lower-carbon electricity production. There is therefore **very high** confidence in this statement.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 18: Midwest

Key Message Process: See Key Message #1.

Key Message #5/6	**Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.**
Description of evidence	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Winkler et al. 2012). Technical Input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for extreme weather and increased precipitation across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Messages 5,6,7) and its Traceable Accounts. Specific details for the Midwest are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012) with its references. Pryor (2012) also contains chapters detailing the most current evidence for the region. There is compelling evidence that annual total precipitation has been increasing in the region, with wetter winter and springs, dryer summers, an increase in extreme precipitation events, and changes in snowfall patterns. These observations are consistent with climate model projections. Both the observed trends and climate models suggest these trends will increase in the future. Recent records also indicate evidence of a number of high impact flood events in the region. Heavy precipitation events cause increased kinetic energy of surface water and thus increase erosion. Heavy precipitation events in the historical records have been shown to be associated with discharge of partially (or untreated) sewage due to the volumes of water overwhelming combined sewage and overflow systems. Climate downscaling projections tend to indicate an increase in the frequency and duration of extreme events (both heavy precipitation and meteorological drought) in the future.
New information and remaining uncertainties	Precipitation is much less readily measured or modeled than air temperature. Thus both historical tendencies and projections for precipitation are inherently less certain than for temperature. Most RCMs still have a positive bias in precipitation frequency but a negative bias in terms of precipitation amount in extreme events. Flood records are very heterogeneous and there is some ambiguity about the degree to which flooding is a result of atmospheric conditions (e.g. flooding is not solely the result of incident precipitation but is also a complex function of the antecedent conditions, soil moisture and landscape infiltration). A key issue is the future distribution of snowfall. Records indicate that snowfall is decreasing in the southern parts of the region, along with increasing lake effect snow. Climate models predict this trend to increase. There is insufficient knowledge about how this change in snowfall patterns will affect flooding and associated problems. This is most likely to affect the really large spring floods that typically cause the worst flooding in the region. In addition, recent data and climate predictions indicate dryer summer conditions, which could tend to offset the effects of higher intensity summer storms by providing increases storage in the soils. The relative effects of these offsetting trends needs to be assessed. Hydrologic modeling that includes the effects of both the increase in extreme events, changing snow patterns, and shifts in the rainfall patterns is needed to determine the future flooding risks.

	Adaptation measures to reduce soil erosion and CSO events are available and could be widely adopted.
Assessment of confidence based on evidence	There have been improvements in agreement between observed precipitation patterns and model simulations. Also an increase in extreme precipitation events is consistent with first-order reasoning and increased atmospheric water burdens due to increased air temperature. Recent data suggest an increase in flooding in the region but there is uncertainty about how the changing snow patterns will affect flood events in the future. Thus there is **high** confidence in the increase in increased rainfall and extreme precipitation events.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 18: Midwest

Key Message Process: See Key Message #1.

Key Message #6/6	**Climate change will exacerbate a range of risks to the Great Lakes region, including changes in the range and distribution of important commercial and recreational fish species, increased invasive species, declining beach health, and harmful blooms of algae. Declines in ice cover will continue to lengthen the commercial navigation season.**
Description of evidence	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Winkler et al. 2012). Technical Input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for changes in ice cover due to increased temperatures across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 10) and its Traceable Accounts. Specific details for the Midwest are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012) with its references. Pryor (2012) also contains chapters detailing the most current evidence for the region. **Altered fish communities**: Warmer lakes and streams will certainly provide more habitat for warm water species as conditions in northern reaches of the basin become more suitable for warm water fish and vacated by cool and cold water species. However, habitat for cold-water fish, though not expected to disappear, will shrink substantially, though it could also expand in some areas, such as Lake Superior. The effects of climate change on expanding the range of all types of fish is dependent on the availability of forage fish, as higher temperatures also necessitate greater food intake. **Increased abundances of invasive species**: As climate change alters water temperatures, habitat, and fish communities, conditions that once were barriers to alien species become conduits for establishment and spread. This migration will alter drastically the fish communities of the Great Lakes basin. Climate change will likely also heighten the impact of invasive species already present in the Great Lakes basin. Warmer winter conditions, for instance, have the potential to benefit alewife, round gobies, ruffe, sea lamprey, rainbow smelt, and other non-native species, species that have spread rapidly throughout the basin and have already inflicted significant ecological and economic harm. **Increased precipitation, evaporation, and extreme events**: Scientists widely predict an increase in precipitation in the Great Lakes region during the winter, spring, and fall, though much of this increase will occur as extreme weather. The increase in precipitation may be offset by more evaporation in the winter due to reduced ice cover, and more evaporation and evapotranspiration in the summer from heat, though such summer evaporation may not be as significant as previously projected. Extreme events—like intense heat waves, unusually mild winters, severe storms, and lack of ice cover on lakes that normally freeze over—are expected to occur with greater frequency. Both high- and low-flow days in streams are expected to increase 22% and 15%, respectively, by 2100. **Declining beach health and harmful algal blooms**: Extreme events increase runoff, adding sediments, pollutants, and nutrients to the Great Lakes. The Midwest has experienced rising trends in precipitation and runoff. Agricultural runoff, in combination with increased water temperatures, has caused considerable non-point source pollution problems in recent years, with increased phosphorus and nitrogen loadings from farms contributing to more and prolonged occurrences of anoxic

	"dead zones" and harmful, lengthy, and dense algae growth. Stormwater runoff that overloads urban sewer systems during extreme events adds to increased levels of toxic substances, sewage, and bacteria in the Great Lakes, affecting water quality, beach health, and human well-being. Increased storm events caused by climate change will lead to an increase in combined sewer overflows. **Decreased ice cover**: Increasingly clement winters have shortened the time between when a lake freezes and when it thaws. Scientists have documented a relatively constant decrease in Great Lakes ice cover since the 1970s, particularly for lakes Superior, Michigan, Huron, and Ontario. The loss of ice cover on the Great Lakes has both ecological and economic implications. Ice serves to protect shorelines and habitat from storms and wave power. Less ice—coupled with more frequent and intense storms—leaves shores vulnerable to erosion and flooding and could harm property and fish habitat. **Water levels**: The methods of linking climate models to hydrologic models used as the basis for the 2009 NCA that predicted a significant drop in Great Lakes levels by the end of the century have been significantly improved by fully coupling the hydrologic cycle between land, lake, and atmosphere (Lofgren et al. 2011). Without that interaction, (Hayhoe et al. 2010) concluded for continued increases in global emissions (SRES A2 scenario) that increases in winter evaporation from less ice cover and summer evaporation and evapotranspiration from warmer air temperatures would negate increases in precipitation. A recent comprehensive assessment (UGLSB), however, has concluded that with a continuation of current rising emissions trends (A2), the lakes will experience a slight decrease or even a rise in water levels, as the earlier studies tended to overstress the amount of evapotranspiration expected to occur. Although the range of potential future lake levels remains large and includes the earlier projected declining lake levels, scientists project an increase in precipitation in the Great Lakes region (most likely in the form of extreme events), which will contribute to maintenance of or an increase in Great Lakes water levels. However, water level changes are not predicted to be uniform throughout the basin. **<u>Shipping</u>**: Ice cover is expected to decrease dramatically by the end of the century, possibly lengthening the shipping season and, thus, facilitating more shipping activity. Although current science suggests water levels in the Great Lakes will likely fall slightly or might even rise over the short run, with even a small drop, climate change could make the costs of shipping increase substantially. For instance, for every inch of draft a 1000-foot ship gives up, its capacity is reduced by 270 tons. Lightened loads today already add about $200,000 in costs to each voyage.
New information and remaining uncertainties	Key issues (uncertainties) are: Water levels are influenced by the amount of evaporation from decreased ice cover and warmer air temperatures and evapotranspiration from warmer air temperatures, compared to potential increases in inflow from more precipitation. Uncertainties about Great Lakes water levels are high, though most models suggest that the decrease in ice cover will lead to slightly lower water levels, beyond natural fluctuations. While the spread of invasive species into the system is near-certain (given the rate of introductions over the previous 50 years) without major policy and regulatory changes, the changes in Great Lakes fish communities are based on extrapolation of known fishery responses to expected changing conditions in the basin. Moreover, many variables beyond water temperature and condition affect fisheries, not the least of which is the availability of forage fish. Higher water temperatures

	necessitate greater food intake, yet the forage base is changing rapidly in many parts of the Great Lakes basin, thus making the projected impact of climate change on fisheries difficult to discern with very high certainty.
Assessment of confidence based on evidence	Peer reviewed literature about the effects of climate change are in broad agreement that air and surface water temperatures are rising and will continue to do so, that ice cover is declining steadily, and that precipitation and extreme events are on the rise. These changes have well-documented effects on large lake ecosystems, such as effects on algal production, stratification, beach health, and fisheries. Key uncertainties exist about Great Lakes water levels and the impact of climate change on fisheries. Given the evidence and remaining uncertainties, there is **very high** confidence in this key message, except **high** confidence for lake levels changing.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
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19. Great Plains

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Key Messages

1. **Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.**
2. **Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events are already observed; as these trends continue, they will require new agriculture and livestock management practices.**
3. **Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.**
4. **Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.**
5. **The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.**

Introduction

The Great Plains is a diverse region where climate and water are woven into the fabric of life. Day-to-day, month-to-month, and year-to-year changes in the weather can be dramatic and challenging. The region experiences multiple climate and weather hazards, including floods, droughts, severe storms, tornadoes, hurricanes, and winter storms. In much of the Great Plains, too little precipitation falls to replace that needed by humans, plants, and animals. Climate variability already stresses communities and causes billions of dollars in damage; climate change will add to both stress and costs.

The people of the Great Plains historically have adapted to this challenging climate. Although trends and projections suggest more frequent and more intense droughts, severe rainfall events, and heat waves, communities and individuals can reduce vulnerabilities through the use of new technologies, community-driven policies, and the judicious use of resources. Adaptation (means of coping with changed conditions) and mitigation (reducing emissions of heat-trapping gases to reduce the speed and amount of climate change) choices can be locally driven, cost effective, and beneficial for local economies and ecosystem services.

Significant climate-related challenges are expected to involve: 1) resolving increasing competition among land, water, and energy resources; 2) developing and maintaining sustainable agricultural systems; 3) conserving vibrant and diverse ecological systems; and 4) enhancing the livelihoods of the region's people. These growing challenges will unfold against a changing backdrop that includes a growing urban population and declining rural population, new economic factors that drive incentives for crop and energy production, advances in technology, and shifting policies such as those related to farm and energy subsidies.

The Great Plains region features relatively flat plains that increase in elevation from sea level to more than 5,000 feet at the base of mountain ranges along the continental divide. Forested mountains cover western Montana and Wyoming, extensive rangelands spread throughout the Plains, marshes extend along Texas' Gulf Coast, and desert landscapes distinguish far west Texas (Omernik 1987). A highly diverse climate results from the region's large north-south extent and change of elevation. This regional diversity also means that climate change impacts will vary across the region.

Great Plains residents already must contend with weather challenges from winter storms, extreme heat and cold, severe thunderstorms, drought, and flood-producing rainfall. Texas' Gulf Coast averages about three tropical storms or hurricanes every four years (Roth 1997), generating coastal storm surge and sometimes bringing heavy rainfall and damaging winds hundreds of miles inland.

Annual average temperatures range from less than 40ºF in the mountains of Wyoming and Montana to more than 70ºF in south Texas, with extremes ranging from –70ºF in Montana to 121ºF in North Dakota and Kansas (NCDC 2012). Summers are long and hot in the south; winters are long and often severe in the north. North Dakota's increase in annual average temperature is the fastest in the contiguous U.S and is mainly driven by warming winters.

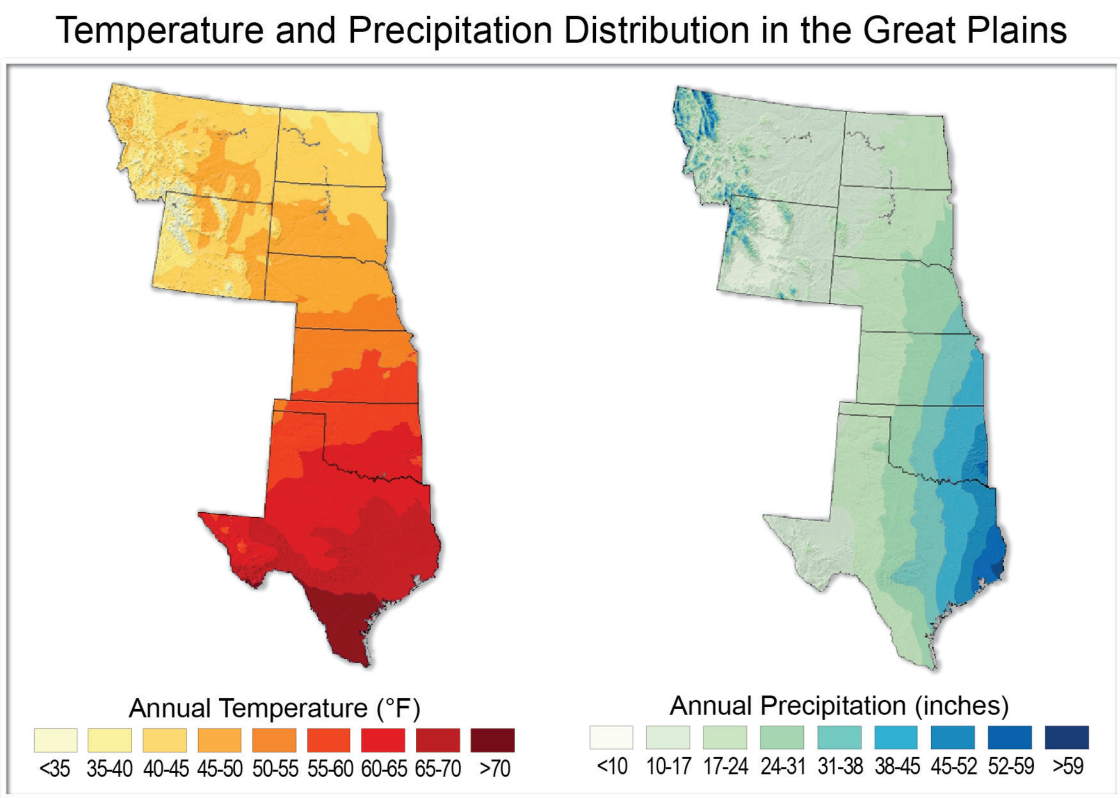

Figure 19.1: Temperature and Precipitation Distribution in the Great Plains

Caption: The region has a distinct north-south gradient in average temperature patterns, with a hotter south and colder north. For precipitation, the regional gradient runs east-west, with a wetter east and a much drier west. (Source: Kunkel et al. 2012b)

Average annual precipitation greater than 50 inches supports lush vegetation in eastern Texas and Oklahoma. For most places, however, average rainfall is less than 30 inches, with some of Montana, Wyoming, and far west Texas receiving less than 15 inches a year. Across much of the region, annual water loss from transpiration by plants and evaporation is higher than annual precipitation, making these areas particularly susceptible to droughts.

Projected Climate Change

For an average of 7 days per year, maximum temperatures reach more than 100ºF in the Southern Plains and about 95ºF in the Northern Plains. These high temperatures are projected to occur much more frequently, even under a scenario of substantial reductions in heat-trapping gas (also called greenhouse gas) emissions (B1), with days over 100ºF projected to double in number in the north and quadruple in the south by mid-century (Kunkel et al. 2012b; Ch. 2: Our Changing Climate; Key Message 7). Similar increases are expected in the number of days with minimum temperatures higher than 80ºF in the south and 60˚F in the north (cooler in mountain regions). These increases in extreme heat will have many negative consequences, including increases in surface water losses, heat stress days, and demand for air conditioning (Ojima et al. 2012). These negative consequences will more than offset the benefits of warmer winters, such as lower winter heating demand, less cold stress on humans and animals, and a longer growing season, which will be extended by an average of 24 days by mid-century (Kunkel et al. 2012b; Ojima et al. 2012; Ch. 2: Our Changing Climate, Key Message 4). More overwintering insect populations are also expected.

There is a projected trend toward increased precipitation in the north and decreased precipitation in the south by the end of this century under a scenario of continued high emissions (A2). In central areas, changes are projected to be small, though the precise location of this transition zone between wetter and drier conditions is not well known, as precipitation projections are less certain than for those for temperature (Kunkel et al. 2012b). The number of days with heavy precipitation (at least one inch) is expected to increase by mid-century, especially in the north. Days with little or no precipitation will also be less common in the north, with projections of up to 5 fewer such days. By contrast, large parts of Texas and Oklahoma are projected to see more days with no precipitation (up to 5 more days with little or no precipitation) in the same timeframe (Kunkel et al. 2012b; Ch. 2: Our Changing Climate; Key Messages 5 & 6).

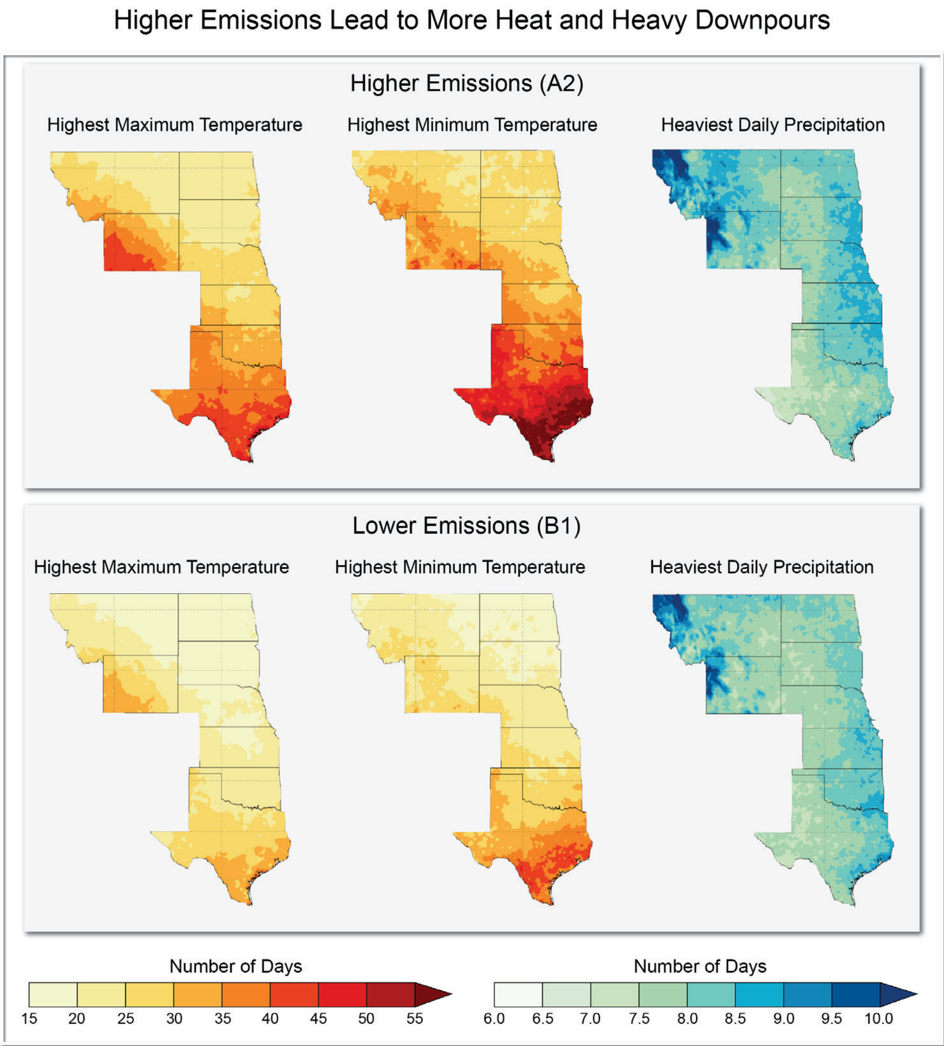

Figure 19.2: Higher Emissions Lead to More Heat and Heavy Downpours

Caption: Maps show projections (for 2041-2070) of the number of days in which highest maximum temperature (left), highest minimum temperature (middle), and heaviest daily precipitation (right) is projected to exceed what was observed between 1971 and 2000 on just 2% of the days in each year, which is about 7 days per year. The top three maps show projected changes if emissions of heat-trapping gases continue to rise (higher emissions, A2), and the bottom three maps show projections with substantial reductions in emissions (lower emissions, B1). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Multi-model Mean.)

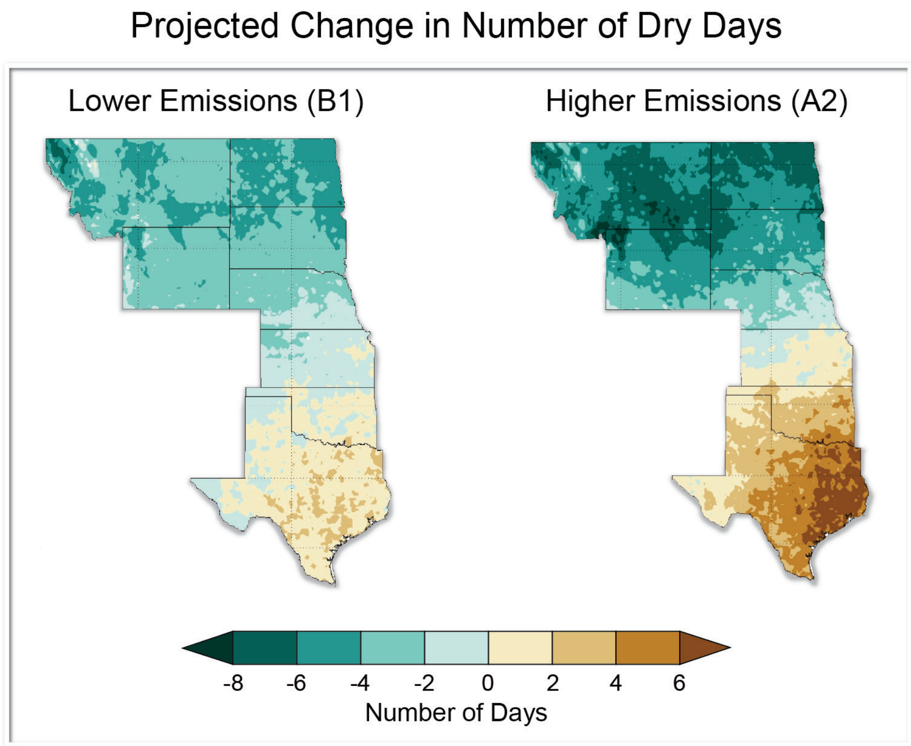

Figure 19.3: Projected Change in the Number of Dry Days, 2071-2099

Caption: Current regional trends of a drier south and a wetter north are projected to become more pronounced, compared to observed 1971 to 2000 averages. Maps show projected changes in the number of days with less than 0.1 inches of precipitation, assuming substantial reductions in emissions (lower emissions, B1) and if emissions continue to rise (higher emissions, A2). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3 Daily Multi-model mean.)

Water, Energy and Land Use

Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.

Water, energy, and land use are inherently interconnected (Barry 1983), and climate change is creating a new set of challenges for these critical sectors (Averyt et al. 2011; Ojima et al. 2002). The Great Plains is rich with energy resources, primarily from coal, oil, and natural gas, with growing wind and biofuel industries (Brekke 2009; Morgan et al. 2008). Texas produces 16% of U.S. energy (mostly from crude oil and natural gas), and Wyoming provides an additional 14% (mostly from coal). North Dakota is the second largest producer of oil in the Great Plains, behind Texas. Nebraska and South Dakota rank third and fifth in biofuel production, and 8 of the top 10 producers of wind energy are from the Great Plains, with Texas topping the list. More than 80% of the region's land area is used for agriculture, primarily cropland, pastures, and rangeland.

Other land uses include forests, urban and rural development, transportation, conservation, and industry.

Significant amounts of water are used to produce energy (Averyt et al. 2011; Foti et al. 2011) and to cool power plants (Barber 2009; Kenny et al. 2009). Electricity is consumed to collect, purify, and pump water. Although hydraulic fracturing to release oil and natural gas is a small component of total water use (Nicot and Scanlon 2012), it can be a significant proportion of water use in local and rural groundwater systems. Energy facilities, transmission lines, and wind turbines can fragment both natural habitats and agriculture lands (Ojima et al. 2002; Ch. 10: Water, Energy & Land).

The trend toward more dry days and higher temperatures across the south will increase evaporation, decrease water supplies, reduce electricity transmission capacity, and increase cooling demands. These changes will add stress to limited water resources and affect management choices related to irrigation, municipal use, and energy generation. In the Northern Plains, warmer winters will reduce heating demand, though hotter summers will increase demand for air conditioning, with the summer increase in demand outweighing the winter decrease (Ch. 4: Energy Supply and Use, Key Message 2).

Changing extremes in precipitation are projected across all seasons, including higher likelihoods of both increasing heavy rain and snow events and more droughts (Kunkel et al. 2012b). Increased runoff and flooding will reduce water quality and erode soils. Increased snowfall, rapid spring warming, and intense rainfall can combine to produce devastating floods, as is already common along the Red River of the North. More intense rains will contribute to urban flooding.

Increased drought frequency and intensity can turn marginal lands into deserts. Reduced per capita water storage will continue to increase vulnerability to water shortages (Texas Water Development Board 2012). Legal requirements mandating water allocations for ecosystems and endangered species add further competition for water resources.

Diminishing water supplies and rapid population growth are critical issues in Texas. Because reservoirs are limited and have high evaporation rates, San Antonio has turned to the Edwards Aquifer as a major source of groundwater storage. Nineteen water districts joined to form a Regional Water Alliance for sustainable water development through 2060. The alliance creates a competitive market for buying and selling water rights and simplifies transfer of water rights.

Sustaining Agriculture

Changes to agricultural production systems due to warming winters and changes in the timing and magnitude of rainfall events are already observed; as these trends continue, they will require new agriculture and livestock management practices

The important agricultural sector in the Great Plains, with a total market value of about $92 billion (split almost equally between crops, at 43%, and livestock, at 46%) (USDA 2012), already contends with significant climate variability (Ch 6: Agriculture). Projected changes in climate, and human responses to it, will affect aspects of the region's agriculture, from the many crops that rely solely on rainfall, to the water and land required for increased energy production from plants, such as fuels made from corn or switchgrass (see Ch. 10: Water, Energy, and Land Use).

Water is central to the region's productivity. The High Plains Aquifer, including the Ogallala, is a primary source for irrigation (Maupin and Barber 2005). In the Northern Plains, rain recharges this aquifer quickly, but little recharge occurs in the Southern Plains.

Projected increases in precipitation in the Northern Plains will benefit agricultural productivity by increasing water availability and reducing reliance on irrigation. Rising temperatures will lengthen the growing season, possibly allowing a second annual crop in some places. But warmer winters also pose challenges (Dunnell and Travers 2011; Hu et al. 2005; Wu et al. 2012). Some pests and invasive weeds will be able to survive the warmer winters (Nardone et al. 2010; Van Dijk et al. 2010). Winter crops that leave dormancy earlier are susceptible to spring freezes (NOAA and USDA 2008). Rainfall events already have become more intense (Groisman et al. 2004), increasing erosion and nutrient runoff, and projections are that the frequency and severity of these heavy rainfall events will increase (Karl 2009; NOAA and USDA 2008).

In the Southern Plains, projected declines in precipitation and greater evaporation due to higher temperatures will increase irrigation demand and exacerbate current stresses on agricultural productivity. Increased water withdrawals from the High Plains Aquifer would accelerate depletion of the aquifer and limit the ability to irrigate (Konikow 2011; Scanlon et al. 2010). Shifting from irrigated to dryland agriculture would reduce crop yields by about a factor of two (Colaizzi et al. 2009).

The projected increase in high temperature extremes and heat waves will negatively affect livestock and concentrated animal feeding operations (Hahn et al. 2009; Mader et al. 2009). Shortened dormancy periods for winter wheat will lessen an important source of feed for the livestock industry. Climate change may thus result in a northward shift of crop and livestock production in the region. In areas projected to be hotter and drier in the future, maintaining agriculture on marginal lands may become too costly.

Adding to climate change related stresses, growing water demands from large urban areas are also placing stresses on limited water supplies. Options considered in some areas include groundwater development and purchasing water rights from agricultural areas for transfer to cities (Grafton et al. 2011).

During the drought of 2011 and 2012, ranchers liquidated large herds due to lack of food and water. Many cattle were sold to slaughterhouses; others were relocated to other pastures through sale or lease. As herds are being rebuilt, there is an opportunity to improve genetic stock, as those least adapted to the drought conditions were the first to be sold or relocated. Some ranchers also used the drought as an opportunity to diversify their portfolio, managing herds in both Texas and Montana.

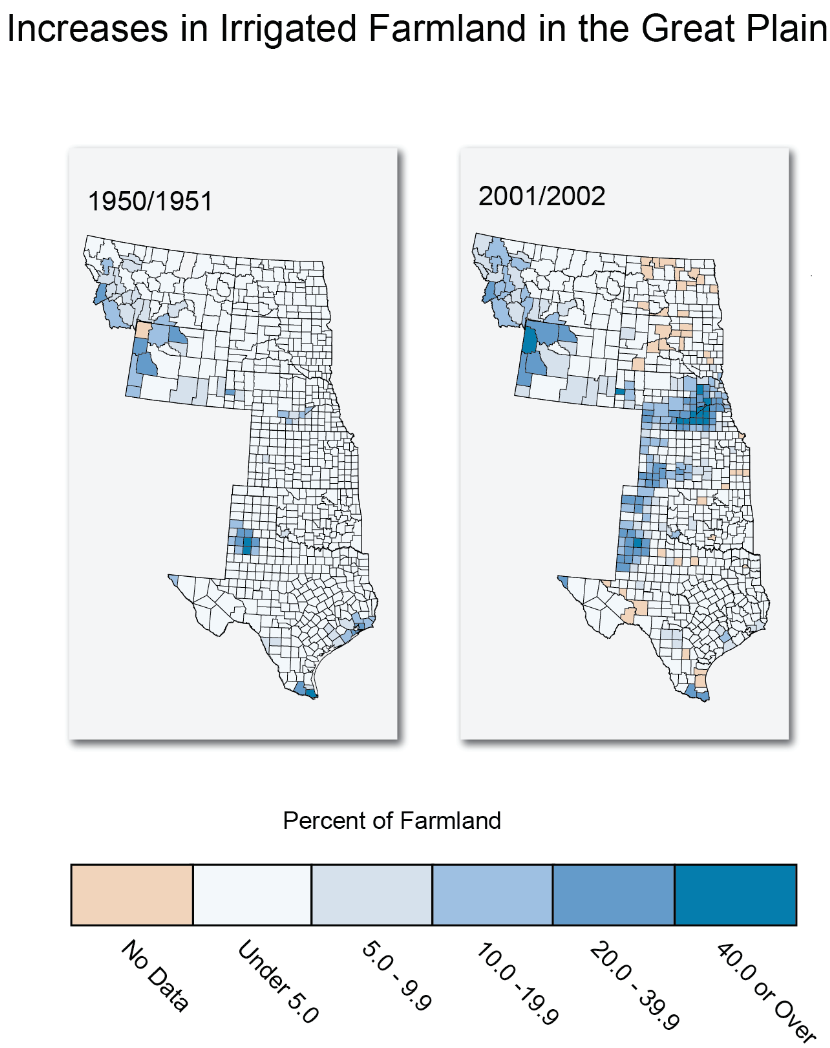

Figure 19.4: Increases in Irrigated Farmland in the Great Plains

Caption: Irrigation in western Kansas, Oklahoma, and Texas supports crop development in semi-arid areas. Declining aquifer levels threaten the ability to maintain production. Some aquifer-dependent regions, like south-eastern Nebraska, have seen steep rises in irrigated farmland, from around 5% to more than 40%, during the period shown. (Source: Atlas of the Great Plains 2011).

Conservation and Adaptation

Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.

Development of lands for energy production, land transformations on the fringes of urban areas, and economic pressures to remove lands from conservation easements pose threats to natural systems in the Great Plains. Habitat fragmentation is already a serious issue that inhibits the ability of species to migrate as climate variability and change alter local habitats (Becker et al. 2007; Gray et al. 2004). Lands that do remain out of production are susceptible to invasion from non-native plant species.

Many plant and animal species are responding to rising temperatures by shifting their distributions at increasingly greater rates (Chen et al. 2011; Parmesan 2007). The historic bison herds migrated to adapt to climate, disturbance, and associated habitat variability (Samson et al. 2004), but modern land-use patterns, roads, agriculture, and structures inhibit similar large-scale migration (H. John Heinz III Center for Science Energy and the Environment 2008; Kostyack et al. 2011). In the Southern Plains, agriculture practices have modified more than 70% of seasonal lakes larger than 10 acres (Guthery and Bryant 1982; Matthews 2008), affecting bird populations (Peterson 2003) and fish populations in the region (Poff et al. 2002; Snodgrass et al. 2001).

Observed climate-induced changes have been linked to changing timing of flowering, increases in wildfire activity and pest outbreaks, shifts in species distributions, declines in the abundance of native species, and the spread of invasive species (Ch 8: Ecosystems & Biodiversity). From Texas to Montana, altered flowering patterns because of more frost-free days have increased the length of pollen season for ragweed by as many as 16 days (Ziska 2011). Earlier snowmelt in Wyoming (Hendricks 2003) has been related to the American pipit songbird laying eggs about 5 days earlier. During the past 70 years, observations indicate that winter wheat is flowering 6 to 10 days earlier as spring temperatures have risen (Hu et al. 2005). Some species may be less sensitive to changes in temperature and precipitation, causing first flowering dates to change for some species but not for others (Dunnell and Travers 2011). Even small shifts in timing, however, can disrupt the integrated balance of ecosystem functions like predator-prey relationships, mating behavior, or food availability for migrating birds.

Box: Climate and Conservation

The interaction of climate and land-use changes across the Great Plains promises to be challenging and contentious. Opportunities for conservation of native grasslands, including species and processes, depend primarily and most immediately on managing a fragmented network of untilled prairie. Restoration of natural processes, conservation of remnant species and habitats, and consolidation/connection of fragmented areas will facilitate conservation of species and ecosystem services across the Great Plains. However, climate change will complicate current conservation efforts as land fragmentation continues to reduce habitat connectivity, as seen in this example of sage grouse habitat.

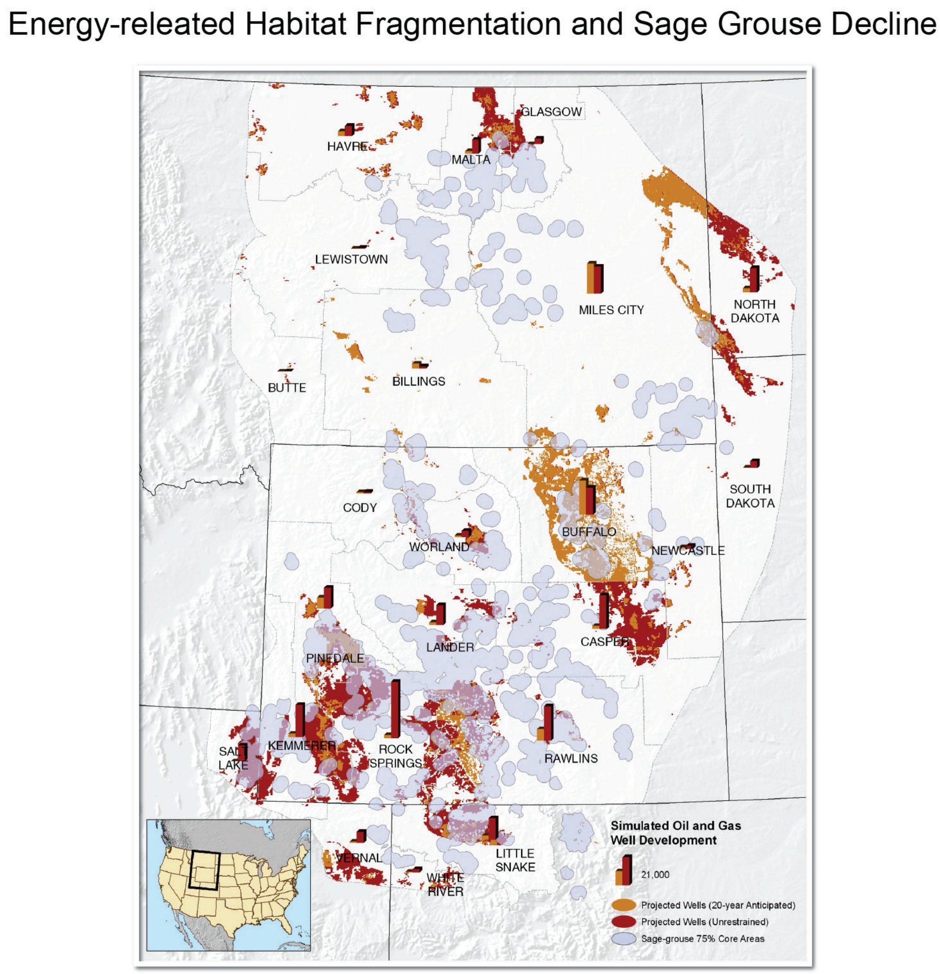

Figure 19.5: Energy-related Habitat Fragmentation and Sage Grouse Decline

Caption: Habitat fragmentation inhibits the ability of species such as Sage Grouse to migrate in response to climate change. Map illustrates the location and extent of expected future oil and gas development in two projected build-out cases. The first utilizes 20-year development projections from the federal Bureau of Land Management, which issues permits for energy development on these lands (orange), and the second assumes unrestrained growth in oil and gas development (red). Blue areas indicate core sage grouse habitat (Doherty 2008) to highlight expected areas of future conflict. Analysis suggests a 7% to 19% population decline in sage grouse populations depending on the build-out scenario. The Greater Sage Grouse is a candidate for Endangered Species Act protections, and its habitat is associated with other species' health as well. (Copeland et al. 2009)

-- end box --

The complicated mix of species range shifts, changing plant cycles, and other climate-related effects make it difficult to project all of the interactions among the vegetative species of the

Great Plains. In general, plants will benefit from higher temperatures, carbon dioxide enrichment, and increases in precipitation, but those benefits will be limited by availability of water in the soil and other factors. The net effect of this set of factors on natural areas of the region is still difficult to project. However, the implementation of ecosystem adaptive management approaches provides robust options for multiple situations.

Vulnerable Communities

Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.

The Great Plains is home to a geographically, economically, and culturally diverse population. For rural and tribal communities, their remote locations, sparse development, limited local services, and language barriers present greater challenges in responding to climate extremes. Working-age people are moving to urban areas, leaving a growing percentage of elderly people in rural communities (See also Ch. 13: Rural Communities).

Overall population throughout the region is stable or declining, with the exception of substantial increases in urban Texas and in tribal communities (Parton et al. 2007). Growing urban areas require more water, expand into forests and cropland, fragment habitat, and are at a greater risk of wildfire – all factors that interplay with climate.

Populations such as the elderly, low-income, and non-native English speakers face heightened climate vulnerability. Public health resources, basic infrastructure, adequate housing, and effective communication systems are often lacking in communities that are geographically, politically, and economically isolated (Singer 2009). Elderly people are more vulnerable to extreme heat, especially in warmer cities and communities with minimal air conditioning or sub-standard housing (Longstreth 1999). Language barriers for Hispanics may impede their ability to plan for, adapt to, and respond to climate-related risks (Johnson and Lichter 2008; Kandel and Parrado 2005; Vazquez-Leon 2009).

The 70 federally recognized tribes in the Great Plains are diverse in their land use, with some located on lands reserved from their traditional homelands, and others residing within territories designated for their relocation, as in Oklahoma. While tribal communities have adapted to climate change for centuries, they are now constrained by physical and political boundaries (Therrell and Trotter 2011; Tsosie 2007). Traditional ecosystems and native resources no longer provide the support they used to (Cook 2008; Tsosie 2009). Tribal members have reported the decline or disappearance of culturally important animal species like bison, changes in the timing of cultural ceremonies due to earlier onset of spring, and the inability to locate certain types of ceremonial wild plants (Riley 2011; Ch. 12: Tribal Lands & Resources).

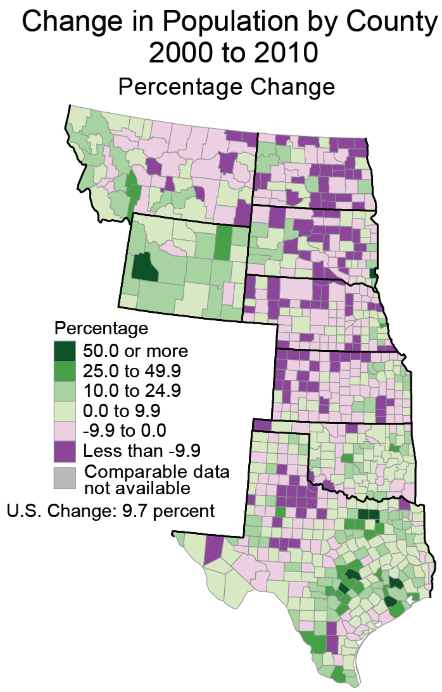

Figure 19.6: Population Change in the Great Plains, 2000-2010.

Caption: Demographic shifts continue to reshape communities in the Great Plains, with many central Great Plains communities losing residents. Rural and tribal communities will face additional challenges in dealing with climate change impacts due to demographic changes in the region. Green areas are increasing in population, while purple areas are decreasing in population. (U.S. Census Bureau 2010b)

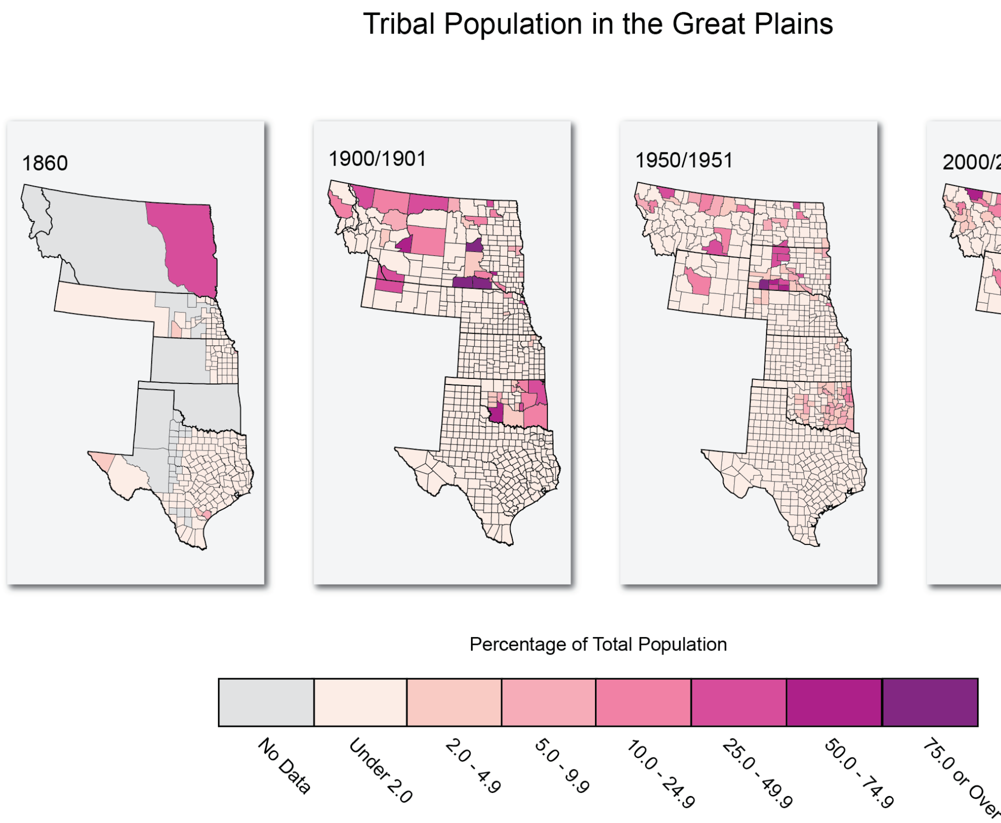

Figure 19.7: Tribal Population in the Great Plains

Caption: Tribal population in the Great Plains is concentrated near large reservations, like the Hopi and Navajo lands in Northern New Mexico; Cherokee, Chickasaw, Choctaw, and other tribal lands in Oklahoma; various Sioux tribes in South Dakota; and Blackfeet and Crow reservations in Montana. (Source: Atlas of the Great Plains2011)

Box: Oglala Lakota Respond to Climate Change

The Oglala Lakota tribe in South Dakota is incorporating climate change adaptation and mitigation planning as they consider long-term sustainable development planning. Their *Oyate Omniciye* plan is a partnership built around six livability principles related to transportation, housing, economic competitiveness, existing communities, federal investments, and local values. Interwoven with this is a vision that incorporates plans to reduce future climate change and adapt to future climate change, while protecting cultural resources (Oyate Omniciye 2011).

-- end box –

Opportunities to Build Resilience

The magnitude of expected changes will exceed those previously experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.

The Great Plains is an integrated system. Changes in one part, whether driven by climate or by human decisions, affect other parts. Some of these changes are already underway, and many pieces of independent evidence project that ongoing climate-related changes will ripple throughout the region.

Many of these challenges will cut across sectors: water, land use, agriculture, energy, conservation, and livelihoods. Competition for water resources will increase within already-stressed human and ecological systems, particularly in the Southern Plains, affecting crops, energy production, and how well people, animals, and plants can thrive. The region's ecosystems, economies, and communities will be further strained by increasing intensity and frequency of floods, droughts, and heat waves that will penetrate into the lives and livelihoods of Great Plains residents. Although some communities and states have made efforts to plan for these projected changes, the magnitude of the adaptation and planning efforts do not match the magnitude of the expected changes.

Successful adaptation of human and natural systems to climate change will require:

- recognition and commitment to addressing these challenges;
- regional-scale planning and local-to-regional implementation (Adger et al. 2011; Joyce et al. 2009; Ojima et al. 2002);
- renewed emphasis on restoration of ecological systems and processes (Eriksen and Brown 2011a; Eriksen 2011b; Eriksen and O'Brien 2007; McNeeley 2011; O'Brien and Leichenko 2008);
- recognition of the value of natural systems to sustaining life (Berkes and Folke 1998; Gunderson and Holling 2002; Tschakert et al. 2007; Walker and Meyers 2004);
- sharing information between decision-makers; and
- enhanced alignment of social and ecological goals (Lyytimäki and Hildén 2007).

Communities already face tradeoffs in efforts to make efficient and sustainable use of their resources. Jobs, infrastructure, and tax dollars that come with fossil fuel extraction or renewable energy production are important, especially for rural communities. There is also economic value in the conversion of native grasslands to agriculture. Yet the tradeoffs between this development, the increased pressure on water resources, and the effects on conservation need to be considered if the region is to develop climate-resilient communities.

Untilled prairies used for livestock grazing provide excellent targets for native grassland conservation. Partnerships among many different tribal, federal, state, local, and private landowners can decrease landscape fragmentation and help manage the connection between agriculture and native habitats. Soil and wetland restoration enhances soil stability and health, water conservation, aquifer recharge, and food sources for wildlife and cattle. Healthy species and ecosystem services support social and economic systems where local products, tourism, and culturally significant species accompany large-scale agriculture, industry, and international trade as fundamental components of society.

There is tremendous adaptive potential among the diverse communities of the Great Plains. Positive steps toward greater community resilience have been achieved through local and regional collaboration and increased two-way communication between scientists and local decision-makers. Climate-related challenges can be addressed with creative local engagement and prudent use of community assets (Ostrom 1990). These assets include social networks, social capital, indigenous and local knowledge, and informal institutions.

Box: The Summer of 2011

Future climate change projections include more precipitation in the northern Great Plains and less in the southern Great Plains. In 2011, such a pattern was strongly manifest, with exceptional drought and recording-setting temperatures in Texas and Oklahoma and flooding in the northern Great Plains. Many locations in Texas and Oklahoma experienced more than 100 days over 100ºF. Both states set new records for the hottest summer since record keeping began in 1895. Rates of water loss were double the long-term average. The heat and drought depleted water resources and contributed to more than $10 billion in direct losses to agriculture alone. The community of Spicewood, Texas ran dry.

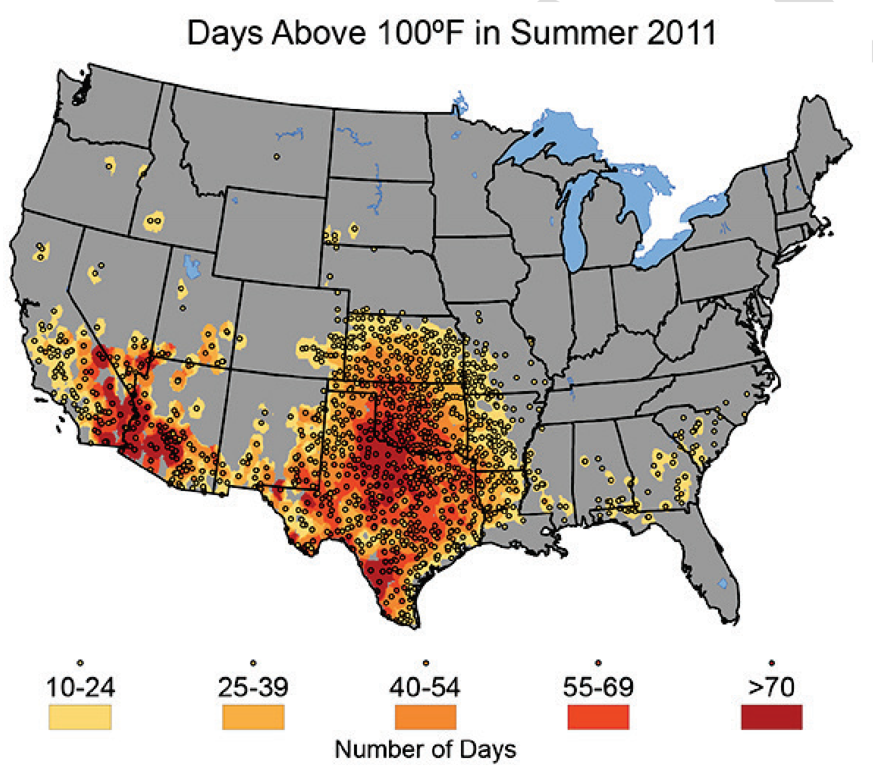

Figure 19.8: Days Above 100ºF in Summer 2011

Caption: In 2011, cities including Houston, Dallas, Austin, Oklahoma City, and Wichita, among others, all set records for the highest number of days recording temperatures of 100ºF or higher in those cities' recorded history. The black circles denote the location of observing stations used in the analysis (those recording 100ºF days) (Source: NCDC 2012)

By contrast, the Northern Plains were exceptionally wet, with Montana and Wyoming recording all-time wettest springs and the Dakotas and Nebraska not far behind. Record rainfall and snowmelt combined to push the Missouri River beyond its banks and leave much of the Crow Reservation in Montana underwater. The Souris River near Minot, North Dakota crested at four feet above its previous record, with a flow five times greater than any in the past 30 years. Losses from the flooding were estimated at $2 billion.

Although there is large natural variability, these recent temperature extremes were attributable in part to human-induced climate change (approximately 20% of the heat wave magnitude and a doubling of the chance that it would occur)(Hoerling et al. 2012a). In the future, average temperatures in this region are expected to increase (Ch. 2: Our Changing Climate, Key Message 8) and will continue to contribute to the intensity of heat waves.

-- end box --

Traceable Accounts

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Key Message Process: A central component of the assessment process was the Great Plains Regional Climate assessment workshop that was held in August, 2011 in Denver, CO with approximately 40 attendees; it began the process leading to a foundational TIR report, the Great Plains Regional Climate Assessment Technical Report (Ojima et al. 2012). The report consists of 18 chapters assembled by 37 authors representing a wide range of inputs including governmental agencies, NGOs, tribes and other entities.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful review of the foundational TIR (Ojima et al. 2002) and of approximately 50 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions were followed by expert deliberation of draft key messages by the authors during an in-person meeting in Kansas City in April 2012 wherein each message was defended before the entire author team before this key message was selected for inclusion in the Report; these discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities".

Key message #1/5	**Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Ojima et al. 2012). Technical Input reports (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for rising temperatures across the U.S. are discussed in Ch. 2: Our Changing Climate, Key message 4 and its Traceable Accounts. Specific details for the Great Plains are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012b) references. The impact of rising temperatures on energy and water is also explored in depth in Ch.10: Water, Energy, and Land, as well as Ch. 4: Energy Supply and Use. Cited publications have explored the projected increase in water competition and stress for natural resources (Averyt et al. 2011; Barber 2009; Kenny et al. 2009; Nicot and Scanlon 2012; Texas Water Development Board 2012) and the fragmentation of natural habitats and agricultural lands (Ojima et al. 2002), providing numerous references that were drawn from to lead to this conclusion.
New information and remaining uncertainties	A key uncertainty is the exact rate and magnitude of the projected changes in precipitation since high inter-annual variability may either obscure or highlight the long-term trends over the next few years. Also unknown is ecological demand for water. Water use by native and invasive species under current climate needs to be quantified so that it can be modeled under future scenarios to map out potential impact envelopes. There is also uncertainty over the projections of changes to precipitation due to model's difficulty with projections of convective precipitation, which is the primary source of water for most of the Great Plains.
Assessment of confidence based on evidence	**Very High** for all aspects of the key message. The relationship between increased temperatures and higher evapotranspiration is well-established. Model projections of higher temperatures are robust. Confidence is highest for the Southern Plains where competition between sectors, cities and states for future supply is already readily apparent and where population growth (demand-side) and projected

	increases in precipitation deficits is greatest.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #2/5	**Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events are already observed; as these trends continue they will require new agriculture and livestock management practices.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Great Plains Technical Input (Ojima et al. 2012). Technical Input reports (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence for altered precipitation across the U.S. are discussed in Ch. 2: Our Changing Climate, Key message 5 & 6 and its Traceable Accounts. Specific details for the Great Plains, such as warming winters and altered rainfall events are detailed in the NCA Climate Trends and Outlooks (Kunkel et al. 2012b) with its references. Limitations of irrigation options in the High Plains aquifer are detailed in Scanlon et al. (2010). The impacts of shifting from irrigated to rain-fed agriculture are detailed in Colaizzi et al.(2009).
New information and remaining uncertainties	A key issue (uncertainty) is rainfall patterns. Although models show a general increase in the northern plains and a decrease in the southern plains, the diffuse gradient between the two leaves the location of greatest impacts on the hydrologic cycle uncertain. Timing of precipitation is critical to crop planting, development and harvesting; shifts in seasonality of precipitation need to be quantified.
Assessment of confidence based on evidence	The general pattern of precipitation changes and overall increases in temperature are robust. However, trying to assess changes in more specific locations is more uncertain, but the implications of these changes are enormous. Our assessment of high is based on the projections and known relationships to crops (e.g. corn not being able to 'rest' at night due to high minimum temperatures), but pinpointing where these will occur is difficult. Additionally, other factors that influence productivity, such as genetics, technological change, economic incentives, and federal and state policies, can alter or accelerate the impacts, which leads to an overall confidence of **high**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/5	**Landscape fragmentation is increasing, for example, in the context of energy development activities. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Great Plains Technical Input (Ojima et al. 2012). Technical Input reports (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. A number of publications have explored the change in habitat composition (Guthery and Bryant 1982), plant distribution and development cycles (Dunnell and Travers 2011; Hu et al. 2005; Ziska 2011) and animal distributions (Chen et al. 2011; H. John Heinz III Center for Science Energy and the Environment 2008; Hendricks 2003; Kostyack et al. 2011; Parmesan 2007).
New information and remaining uncertainties	In general, the anticipated carbon dioxide enrichment, warming, and increase in precipitation variability influence vegetation primarily by affecting soil-water availability to plants, especially given the current east-to-west difference in precipitation and the vegetation it supports. These effects are evident in experiments with each of the individual aspects of climate change. It is difficult to project, however, all of the interactions with all of the vegetative species of the Great Plains so as to better manage ecosystems. Several native species have been in decline due to habitat fragmentation, including quail, ocelots and lesser prairie chickens. Traditional adaptation methods of migration common to the Great Plains, such as bison herds had historically done, are less of an option as animals are confined to particular locations. As the content of habitats change due to invasive species of plant and animals and viability of native vegetation as climate changes, the current landscapes may be incapable of supporting these populations.
Assessment of confidence based on evidence	**High**. The effects of carbon dioxide and water availability are well known on individual species, but less published research exists on the interaction between different species.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #4/5	**Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Ojima et al. 2012). Technical Input reports (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Extreme events are documented in Key Message 7 from the "Our Changing Climate" chapter (Ch. 2) for the Nation, and in Kunkel et al. (2012b) for specific outlooks and trends for this region. There are a few studies documenting the vulnerability of communities in remote locations with sparse infrastructure, limited local services, and aging population (Singer 2009) with some areas inhibited by language barriers (Johnson and Lichter 2008; Kandel and Parrado 2005; Vazquez-Leon 2009). Changes in the tribal communities have been documented on a number of issues (Cook 2008; Oyate Omniciye 2011; Riley 2011; Therrell and Trotter 2011; Tsosie 2007, 2009).
New information and remaining uncertainties	A key issue (uncertainty) is how limited financial resources will be dedicated to adaptation actions and the amount of will and attention that will be paid to decreasing vulnerability and increasing resilience throughout the region. Should the awareness of damage grow great enough, it may overcome the economic incentives for development and change perspectives allowing for increased adaptive response but if current trends continue more vulnerable lands may be lost; thus the outcome on rural and vulnerable populations is largely unknown.
Assessment of confidence based on evidence	**High**. Extensive literature exists on vulnerable populations, limited resources and ability to respond to change. Because the expected magnitude of changes is beyond previous experience, societal response is unknown.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #5/5	**The magnitude of expected changes will exceed those previously experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Great Plains Technical Input (Ojima et al. 2012). Technical Input reports (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. A number of publications have looked at the requirements for adaptation of human and natural systems to climate change concerning the need for large and small scale planning (Adger et al. 2011; Berkes and Folke 1998; Joyce et al. 2009; Ojima et al. 2002), emphasis on restoring ecological systems and processes (Eriksen and Brown 2011a; Eriksen 2011b; Eriksen and O'Brien 2007; McNeeley 2011; O'Brien and Leichenko 2008), realizing the importance of natural systems (Berkes and Folke 1998; Gunderson and Holling 2002; Tschakert et al. 2007; Walker and Meyers 2004), and aligning the social and ecological goals (Lyytimäki and Hildén 2007). The short-term nature of many planning activities is described in Riley et al. (2012).
New information and remaining uncertainties	No clear catalog of ongoing adaptation activities exists for the Great Plains region. Initial steps have been supported by the National Climate Assessment in association with NOAA's Regional Integrated Sciences and Assessments teams. Until a systematic assessment is conducted, most examples of adaptation are anecdotal. However, stresses in physical and social systems are readily apparent as described in the other key messages. How communities, economic sectors, and social groups will respond to these stresses needs further study.
Assessment of confidence based on evidence	**Medium**. Due to the nature of the challenges, the risks of delaying response are tremendous. While systematic evidence is currently lacking, emerging studies point toward a proclivity toward short-term planning and incremental adjustment rather than long-term strategies for evolving agricultural production systems, habitat management, water resources and societal changes.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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20. Southwest

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Key Messages

1. **Snowpack and streamflow amounts are projected to decline, decreasing water supply for cities, agriculture, and ecosystems.**
2. **The Southwest produces more than half the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increased temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.**
3. **Increased warming, due to climate change, and drought have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.**
4. **Flooding and erosion in coastal areas is already occurring and is damaging some areas of the California coast during storms and extreme high tides. Sea level rise is projected to increase, resulting in major damage as wind-driven waves ride upon higher seas and reach further inland.**
5. **Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in Southwestern cities, which are home to more than 90 percent of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.**

Introduction

The Southwest is the hottest and driest region in the U.S., where the availability of water has defined its landscapes, history of human settlement, and modern economy. Climate changes pose challenges for an already parched region that is expected to get hotter and, in its southern half, significantly drier. Increased heat and changes to rain and snowpack will send ripple effects throughout the region's critical agriculture sector, affecting the lives and economies of 56 million people – a population that is expected to increase by 38 million by 2050. Severe and sustained drought will stress water sources already over-utilized in many areas, forcing increasing competition among farmers, urban dwellers, and the region's varied plant and animal life for the region's most precious resource.

The region's populous coastal cities face rising sea levels, extreme high tides, and storm surges, which pose particular risks to highways, bridges, power plants, and sewage treatment plants. Climate challenges also increase risks to critical port cities, which handle half of the nation's incoming shipping containers.

Agriculture, a mainstay of the regional and national economies, faces uncertainty and change. The Southwest produces more than half of the nation's high-value specialty crops, such as vegetables, fruits, and nuts. The severity of future impacts will depend upon the complex interaction of pests, water supply, reduced chilling periods, and more rapid changes in the seasonal timing of crop development due to projected warming and extreme events.

Climate changes will increase stress on the region's rich diversity of plant and animal species. Widespread tree death and fires, which already have caused billions of dollars in economic losses, are projected to increase, forcing wholesale changes to forest types, landscapes, and the communities that depend on them (See also Ch 7: Forestry).

Tourism and recreation, generated by the Southwest's winding canyons, snow-capped peaks, and Pacific Ocean beaches, provide a significant economic force that also faces climate change challenges. The recreational economy will be increasingly affected by reduced streamflow and a shorter snow season, influencing everything from the ski industry to lake and river recreation.

Observed and Projected Climate Change

The Southwest is already experiencing the impacts of climate change. The region has heated up markedly in recent decades, and the period since 1950 has been hotter than any comparably long period in at least 600 years (Ababneh 2008; BCDC 2011; Bonfils et al. 2008; Graumlich 1993; Hoerling et al. 2012; Millar et al. 2006; Salzer and Kipfmueller 2005; Salzer et al. 2009; Stevens et al. 2008; Woodhouse et al. 2010; Ch. 2 Our Changing Climate; Key Message 3). The decade 2001-2010 was the warmest in the 110-year instrumental record, with temperatures almost 2°F higher than historic averages, with fewer cold snaps and more heat waves (Hoerling et al. 2012). Compared to temperature, precipitation trends vary considerably across the region, with portions experiencing both decreases and increases (Hoerling et al. 2012; Ch. 2: Our Changing Climate; Key Message 5). There is mounting evidence that the combination of human-caused temperature increases and recent drought has influenced widespread tree mortality (Allen et al. 2010; Van Mantgem et al. 2009), increased fire occurrence and area burned (Westerling et al. 2006), and forest insect outbreaks (Bentz et al. 2010; Ch. 7: Forestry). Human-caused temperature increases and drought have also caused earlier spring snowmelt and shifted runoff to earlier in the year (Barnett et al. 2008).

Regional annual average temperatures are projected to rise by 2°F to 6°F by 2041-2070 if global emissions are substantially reduced (as in the B1 emission scenario) and by 5°F to 9°F by 2070-2099 with continued growth in global emissions (A2), with the greatest increases in the summer and fall. Summertime heat waves are projected to become longer and hotter, whereas the trend of decreasing wintertime cold snaps is projected to continue (Gershunov et al. 2009; Kodra et al. 2011; Ch. 2: Our Changing Climate; Key Message 7). These changes will directly affect urban public health through increased risk of heat stress, and urban infrastructure through increased risk of disruptions to electric power generation. Rising temperatures also have direct impacts on crop yields and productivity of key regional crops, such as fruit trees.

Projected Temperature Increases

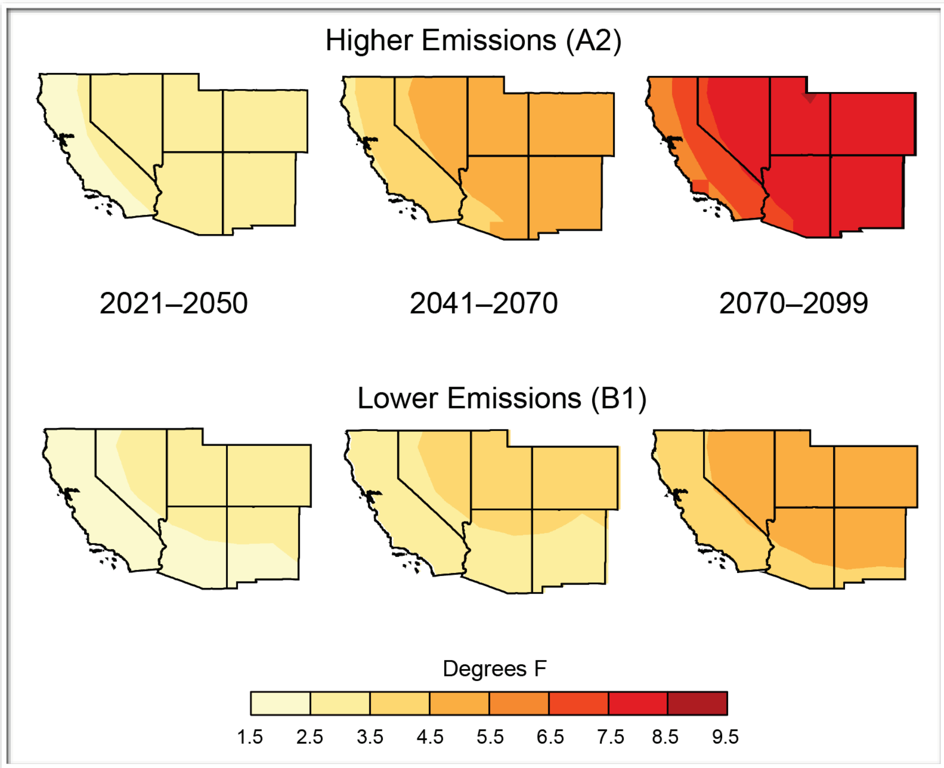

Figure 20.1: Projected Temperature Increases

Caption: Maps show projected changes in average temperature (°F) from observed average temperatures between 1971 and 1999. Top row shows projections assuming heat-trapping gas emissions continue to rise (A2), Bottom row shows projections assuming substantial reductions in emissions (B1). (Figure source: NOAA NCDC / CICS-NC. Data from CMIP3.)

Projections of precipitation changes are less certain than those for temperature (Cayan et al. 2012; Kunkel et al. 2012). Under a high emissions scenario (A2), reduced precipitation is consistently projected for the southern part of the Southwest by 2100, but there is model disagreement on the direction of change in the northern part of the region. Seasonally, significant decreases in spring precipitation in the south are projected, while a mix of increases and decreases are projected for the other seasons and in the north (Kunkel et al. 2012; Ch. 2: Our Changing Climate; Key Message 5). An increase in winter flood hazard risk is projected due to increases in flows of airborne moisture into California's coastal ranges and the Sierra Nevada (Dettinger 2011; Dettinger et al. 2011). These "atmospheric rivers" have contributed to the largest floods in California history (Neiman et al. 2008), and can penetrate inland as far as Utah and New Mexico.

The region has experienced severe, 50-year-long mega-droughts over the past 2000 years. Future droughts are projected to be substantially hotter, and for major river basins, such as the Colorado River Basin, drought is projected to become more frequent, intense, and longer lasting than in the historical record (Cayan et al. 2012). These drought conditions present a huge challenge for regional management of water resources and natural hazards like wildfire. In light of climate change and water resources treaties with Mexico, discussions are underway, and will need to continue into the future, to address demand pressures and vulnerabilities of groundwater and surface water systems that are shared along the border.

Box: Vulnerabilities of Native Nations and Border Cities

The Southwest's 182 federally recognized tribes and communities in its U.S.-Mexico border region share particularly high vulnerabilities to climate changes such as high temperatures, drought, and severe storms. Tribes may face loss of traditional foods, medicines, and water supplies, due to declining snowpack, increasing temperatures, and increasing drought (See also Ch 12: Tribal Lands and Resources). Historic land settlements and high rates of poverty – more than double that of the general U.S. population (Sarche and Spicer 2008) – constrain tribes' abilities to respond effectively to climate challenges.

Most of the Southwest border population is concentrated in eight fast-growing, adjacent cities on either side of the U.S.-Mexico border (like El Paso and Juarez) with shared problems. If the 24 U.S. counties along the entire border were aggregated as a 51st state, they would rank near the bottom in per capita income, unemployment, insurance coverage for children and adults, and high school completion (Soden 2006). Border cities concentrate health and safety risks, such as air pollution, inadequate erosion and flood control, and insufficient safe drinking water.

Lack of financial resources and low tax bases for generating resources have resulted in a lack of roads and safe drinking water infrastructure, which makes it all the more daunting for tribes and border populations to address climate change issues.

-- End box --

Reduced Snowpack and Streamflows

Snowpack and streamflow amounts are projected to decline, decreasing water supply for cities, agriculture, and ecosystems.

Winter snowpack, which slowly melts and releases water in spring and summer, when both natural ecosystems and people have the greatest needs for water, is key to the Southwest's hydrology and water supplies. Over the past 50 years across most of the Southwest, there has been less late winter precipitation falling as snow, earlier snow melt, and earlier arrival of most of the year's streamflow (Hidalgo et al. 2009; Pierce et al. 2008). Streamflow totals in the Sacramento-San Joaquin, the Colorado, the Rio Grande, and in the Great Basin were 5% to 37% lower between 2001 and 2010 than the 20th century average flows (Hoerling et al. 2012). Projections of further reduction of late winter and spring snowpack, and subsequent reductions in runoff and soil moisture (Cayan et al. 2008; Cayan et al. 2010; Christensen and Lettenmaier 2007), pose increased risks to the water supplies needed to maintain the Southwest's cities, agriculture, and ecosystems.

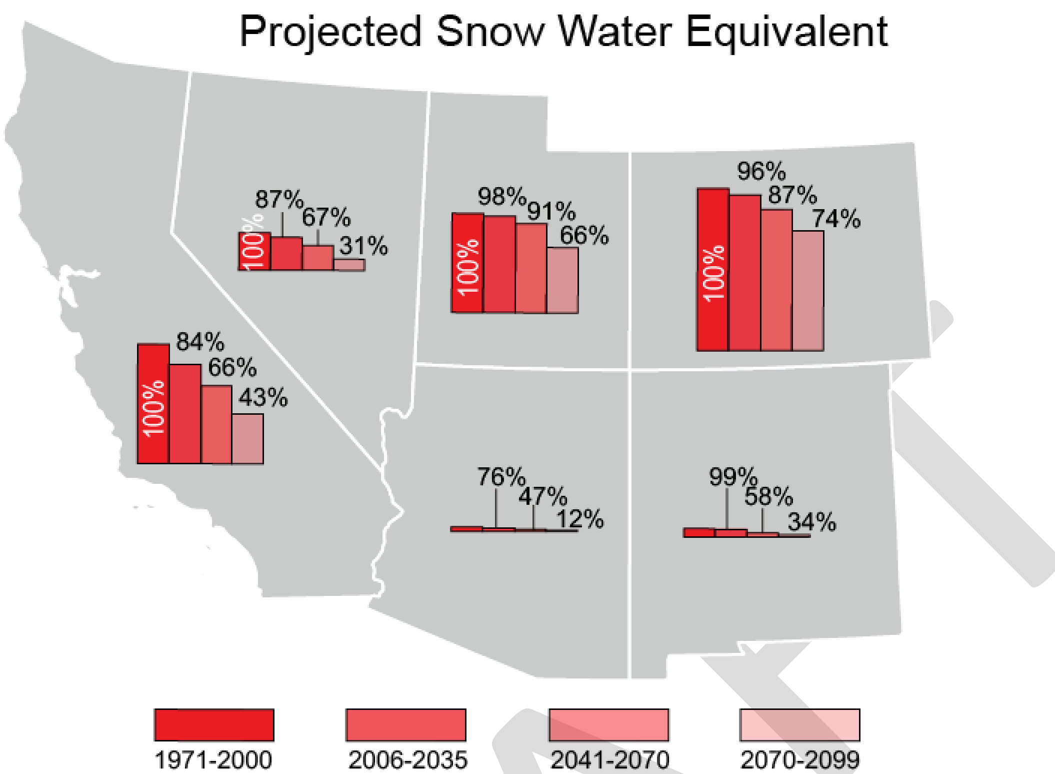

Figure 20.2: Projected Snow Water Equivalent

Caption: Percent changes in statewide snow water equivalent (SWE) accumulation compared to the 1971-2000 modeled average for the first of the month during which the 1971-2000 modeled average modeled peak SWE occurred. Snow water equivalent refers to the amount of water held in a volume of snow, which depends on the density of the snow and other factors. The maps depict the average projections of 16 global climate models for 30-year periods, assuming continued growth in emissions (A2 scenario). The size of bars is in proportion to the amount of snow each state contributes to the regional total; thus, the bars for Arizona are much smaller than those for Colorado, which contributes the most to region-wide snowpack. Declines in peak SWE are strongly correlated with early timing of runoff and decreases in total runoff. For watersheds that depend on snowpack to provide the majority of the annual runoff, such as in the Sierra Nevada and in the Upper Colorado and Upper Rio Grande River Basins, lower SWE generally translates to reduced reservoir water storage. (Source: calculations by Dan Cayan and Mary Tyree (Scripps Institution of Oceanography))

Temperature-driven reductions in snowpack are compounded by dust and soot accumulation on the surface of snowpack. This layer of dust and soot, transported by winds from lowland regions, increases the amount of the sun's energy absorbed by the snow. This leads to earlier snowmelt and evaporation – both of which have negative implications for water supply, alpine vegetation, and forests (Ault et al. 2011; Painter et al. 2010; Painter et al. 2007; Qian et al. 2009). The prospect of more lowland soil drying out from drought and human disturbances (like agriculture and development) make regional dust a potent future risk to snow and water supplies.

In California, drinking water infrastructure needs are estimated at $4.6 billion annually over the next 10 years, even without considering the effects of climate change (ASCE 2012). Climate change will increase the cost of maintaining and improving drinking water infrastructure, because expanded wastewater treatment and desalinating water for drinking are among the key strategies for supplementing water supplies.

Box: The Southwest's Renewable Potential to Produce Energy with Less Water
The Southwest's abundant geothermal, wind, and solar power-generation resources could help transform the region's electric generating system into one that uses substantially more renewable energy. This transformation has already started, driven in part by renewable energy portfolio standards adopted by five of six Southwest states, and renewable energy goals in Utah. California's law limits imports of baseload electricity generation from coal and oil, and mandates reduction of greenhouse gas (also referred to as heat-trapping gas) emissions to 1990 levels by 2020 (California Energy Commission 2011).

As the regional climate becomes hotter and, in parts of the Southwest, drier, there will be less water available for the cooling of thermal power plants (Averyt et al. 2011), which use about 40% of the surface water withdrawn in the U.S. (King et al. 2008). The projected warming of water in rivers and lakes will reduce the capacity of thermal power plants, especially during summer when electricity demand skyrockets (van Vliet et al. 2012). Wind and solar photovoltaic installations could substantially reduce water withdrawals. A large increase in the portion of power generated by renewable energy sources may be feasible at reasonable costs (DOE 2012; Nelson et al. 2012; Wei et al. 2012), and could substantially reduce water withdrawals (Cooley et al. 2011; Halpern and Tramontin 2007; Ch. 10: Water, Energy and Land Use).

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Potential Emissions Reductions in the Electricity Sector

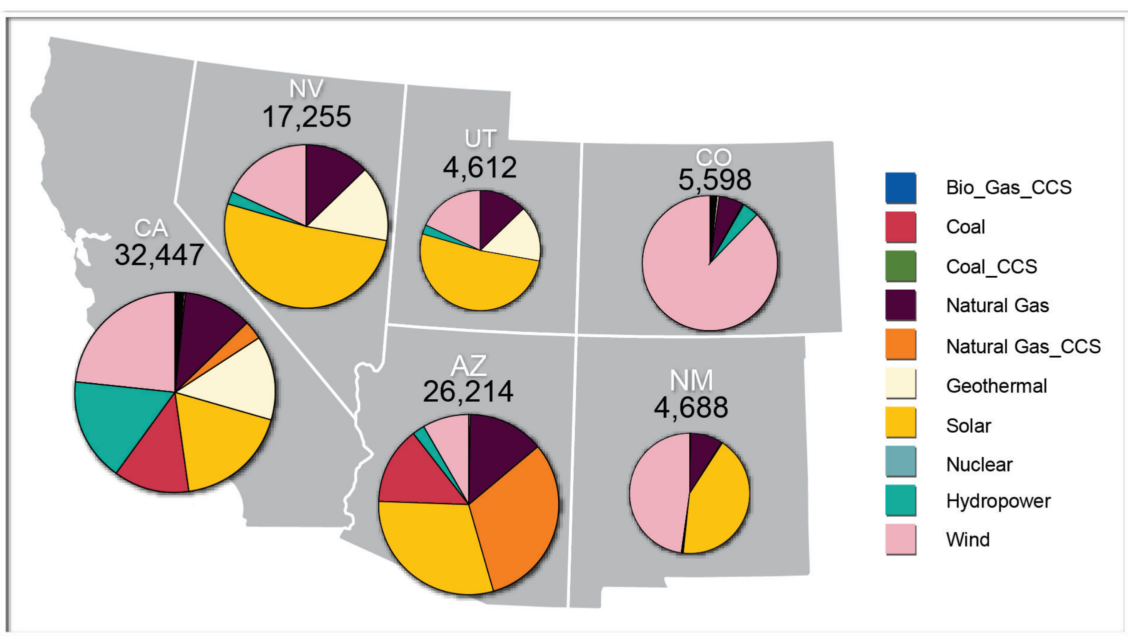


Figure 20.3: Potential Emissions Reductions in the Electricity Sector

Caption: Major shifts in how electricity is produced can lead to large reductions in heat-trapping gas emissions. Many different energy combinations could achieve an 80% reduction of greenhouse gas emissions from 1990 levels in the electricity sector. For each state, that mix varies, with the circle representing the average hourly generation in megawatts (MW; the number above each circle) from 10 potential energy sources. CCS refers to carbon capture and storage. (Source: data from Wei et al. 2012)

Conservation efforts have proven to reduce water use, but are not projected to be sufficient if current trends for water supply and demand continue (Rockaway et al. 2011). Large water utilities are currently attempting to understand how water supply and demand may change in conjunction with climate changes, and which adaptation options are most viable (Means et al. 2010; U.S. Bureau of Reclamation 2011a, 2011b).

Threats to Agriculture

The Southwest produces more than half the nation's high-value specialty crops, which are irrigation-dependent and vulnerable to extremes of moisture, cold, and heat. Increased temperatures threaten to reduce yields, and increasing competition for scarce water supplies will affect rural livelihoods.

Farmers are renowned for adapting to yearly changes in the weather, but climate change in the Southwest could happen faster and more extensively than farmers' ability to adapt. The region's pastures are rain-fed and highly susceptible to projected drought. Excluding Colorado, more than 92% of the region's cropland is irrigated, and agricultural uses account for 79% of all water withdrawals in the region. A warmer, drier climate is projected to accelerate current trends of large transfers of irrigation water to urban areas (Frisvold et al. 2012; Pritchett et al. 2011), which would affect local agriculturally dependent economies.

California produces about 95% of U.S. apricots, almonds, artichokes, figs, kiwis, raisins, olives, cling peaches, dried plums, persimmons, pistachios, olives, and walnuts, in addition to other high-value crops (Beach et al. 2010). Drought and extreme weather affects the market value of fruit and vegetables more than other crops, because they have high water content and because sales depend on good visual appearance (Hatfield et al. 2008). The combination of a longer frost-free season, less frequent cold snaps, and more frequent heat waves accelerates crop ripening and maturity, reduces yields of corn, tree fruit, and wine grapes, stresses livestock, and increases agricultural water consumption (Baldocchi and Wong 2008; Battisti and Naylor 2009; Lobell et al. 2006; Purkey et al. 2008). This combination of climate changes is projected to continue and intensify, possibly requiring a northward shift in crop production, displacing existing growers, and affecting farming communities (Jackson et al. 2012a; Medellín-Azuara et al. 2012).

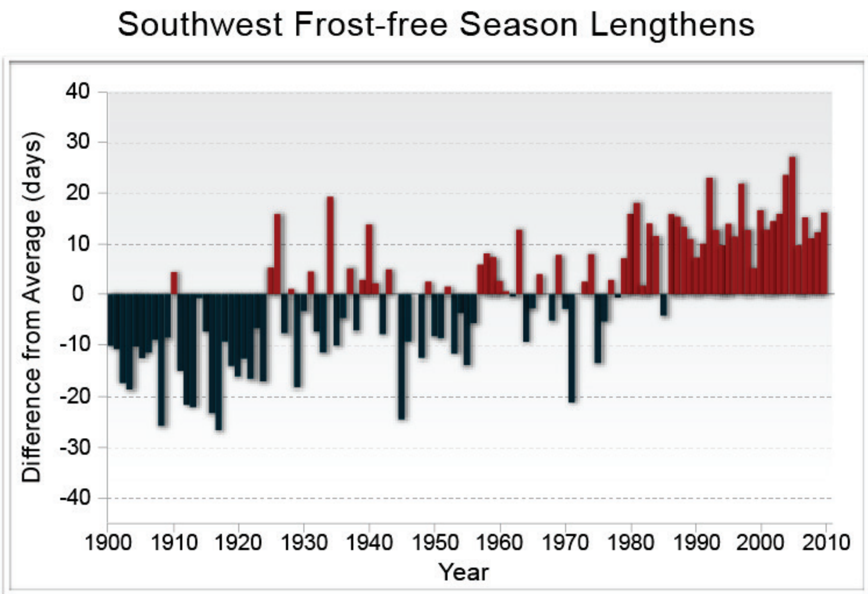


Figure 20.4: Southwest Frost-free Season Lengthens

Caption: The frost-free season is defined as the period between the last occurrence of 32°F in spring and the first occurrence of 32°F in the subsequent fall. The chart shows significant increases in the number of consecutive frost-free days per year in the past three decades, compared to the 1901-2010 average. Increased frost-free season length, especially in already hot and moisture-stressed regions like the Southwest, is projected to lead to further heat stress on plants and increased water demands for crops. (Figure source: modified from (Hoerling et al. 2012),)

Winter chill periods are projected to fall below the duration necessary for many California trees to bear nuts and fruits, which will result in lower yields (Luedeling et al. 2011). Warm-season vegetable crops grown in Yolo County, one of California's biggest producers, may not be viable under hotter climate conditions (Jackson et al. 2012a; Jackson et al. 2012b). Once temperatures increase beyond optimum growing thresholds, further increases in temperature, like those projected for the decades beyond 2050, can cause large decreases in crop yields and hurt the region's agricultural economy.

Increased Wildfire

Increased warming, due to climate change, and drought have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.

Fire naturally shapes southwestern landscapes. Indeed, many Southwest ecosystems depend on periodic wildfire to maintain healthy tree densities, enable seeds to germinate, and reduce pests (Bowman et al. 2009; Keeley and Zedler 2009). Excessive wildfire destroys homes, exposes slopes to erosion and landslides, threatens public health, and causes economic damage (Frisvold et al. 2011; Morton and Global Institute of Sustainable Forestry 2003; Richardson et al. 2011;

WFLC 2010). The $1.2 billion in damages from the 2003 Grand Prix fire in southern California illustrates the high cost of wildfires (WFLC 2010).

Beginning in the 1910s and 1920s, the federal government developed a national policy of extinguishing every fire, which, in hindsight, allowed wood and other fuels to over-accumulate (Hurteau et al. 2008) and urban development to encroach on fire-prone areas. Recent policies that allow some wildfires to burn naturally have increased burned area back to the levels seen before the strict fire controls.

Increased warming due to climate change (Bonfils et al. 2008), drought, insect infestations (Williams et al. 2010), and fuel accumulation make the Southwest vulnerable to increased wildfire. Climate outweighed other factors in determining burned area in the western U.S. from 1916 to 2003 (Littell et al. 2009), a finding confirmed by 3000-year long reconstructions of southwestern fire history (Marlon et al. 2012; Swetnam 1993; Swetnam et al. 2009; Taylor and Scholl 2012; Trouet et al. 2010). Between 1970 and 2003, warmer and drier conditions increased burned area in western U.S. mid-elevation conifer forests by 650% (Westerling et al. 2006).

Drought and increased temperatures due to climate change have caused extensive tree death across the Southwest (Breshears et al. 2005; Van Mantgem et al. 2009). In addition, winter warming due to climate change has exacerbated bark beetle outbreaks by allowing more beetles, which normally die in cold weather, to survive and reproduce (Raffa et al. 2008). Wildfire and bark beetles killed trees across 20% of Arizona and New Mexico forests from 1984 to 2008 (Williams et al. 2010).

Numerous fire models project more wildfire as climate change continues (Gonzalez et al. 2010; Krawchuk et al. 2009; Litschert et al. 2012; Westerling et al. 2012). Models project a doubling of burned area in the southern Rockies, (Litschert et al. 2012) and up to 74% more fires in California (Westerling et al. 2012). Fire contributes to upslope shifting of vegetation and conversion of forests to woodland or grassland (Allen and Breshears 1998; Keeley and Brennan 2012). Historical and projected climate change make 42% of the region vulnerable to these shifts of major vegetation types or biomes; notably threatened are the conifer forests of southern California and sky islands of Arizona (Gonzalez et al. 2010).

Prescribed burning, mechanical thinning, and retention of large trees can help forest ecosystems adapt to climate change (Finney et al. 2005; Stevens et al. 2008; Swetnam et al. 2009). These adaptation measures also reduce emissions of the heat-trapping gases that cause climate change because long-term storage of carbon in large trees outweighs short-term emissions from prescribed burning (Hurteau and Brooks 2011; Hurteau et al. 2008).

Sea Level Rise and Coastal Damage

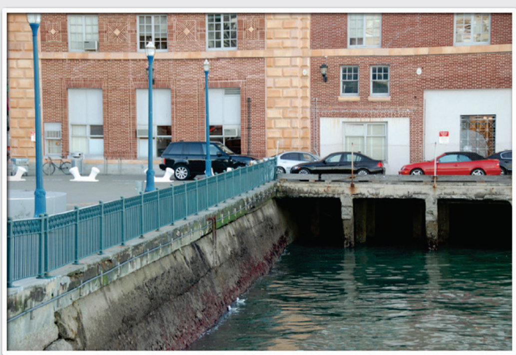
Flooding and erosion in coastal areas is already occurring and is damaging some areas of the California coast during storms and extreme high tides. Sea level rise is projected to increase as the Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher sea levels and reach further inland.

In the last 100 years, sea level has risen along the Southwest coast by 6.7 to 7.9 inches (NRC 2012). In the last decade, high tides on top of this sea level rise have contributed to new damage to infrastructure, such as the inundation of Highway 101 near San Francisco and backup of seawater into the San Francisco Bay Area sewage systems.

Although sea level along the California coast has been relatively constant since 1980, both global and relative Southwest sea levels are expected to increase at accelerated rates (Bromirski et al. 2011; NRC 2012; Parris et al. 2012; Romanovsky et al. 2011). During the next 30 years, the greatest impacts will be seen during high tides and storm events. Rising sea level will allow more wave energy to reach farther inland and extend high tide periods, worsening coastal erosion on bluffs and beaches, and increasing flooding potential (Bromirski et al. 2012; Cayan et al. 2012; Kildow and Colgan 2005; Revell et al. 2012; Storlazzi and Griggs 2000).

The result will be impacts to the nation's largest ocean-based economy, estimated at $46 billion annually (Cooley et al. 2012; Pendleton 2009). If adaptive action is not taken, coastal highways, bridges, and other transportation infrastructure (such as the San Francisco and Oakland airports) are at increased risk of flooding with a 16-inch rise in sea level in the next 50 years (BCDC 2011), an amount consistent with the 1 to 4 feet of expected global increase in sea level (Ch. 2: Our Changing Climate, Key Message 9). In Los Angeles, sea level rise poses a risk to groundwater supplies and estuaries (Bloetscher et al. 2010; Heberger et al. 2009), by potentially contaminating groundwater with seawater, or increasing the costs to protect coastal freshwater aquifers (Webb and Howard 2011).

Coastal Risks Posed by Sea Level Rise and High Tides



1 February 2011: 16:51 -0.47 ft MLLW

20 January 2011: 11:32 7.20 ft MLLW

Figure 20.5: Coastal Risks Posed by Sea Level Rise and High Tides

Caption: Photos show water levels along the Embarcadero in San Francisco, California during relatively normal tides (top), and during an extreme high tide or "king tide" (bottom). King tides, which typically happen twice a year as a result of a gravitational alignment of the sun, moon, and Earth, range from four to nine feet, providing a preview of what California coasts may look like in the future. While king tides are the extreme high tides today, with projected future sea level rise, this level of water and flooding will occur during regular monthly high tides. During storms and future king tides, more coastal flooding and damage will occur. The King Tide Photo Initiative encourages the public to visually document the impact of rising waters on the California coast, as exemplified during current king tide events. (Photo credit: Mark Johnson).

Projected increases in extreme flooding in addition to sea level rise will increase human vulnerability to coastal flooding events. Currently, 140,000 people are at risk from what is considered a once-in-100-year flood. With a sea level rise of about three feet (in the range of projections for this century (NRC 2012; Parris et al. 2012; Ch. 2: Our Changing Climate; Key Message 9), 420,000 people would be at risk from the same kind of 100-year flood event (Cooley et al. 2012). Highly vulnerable populations – people less able to prepare, respond, or recover from natural disaster due to age, race, or income – make up approximately 18% of the at-risk population (Cooley et al. 2012; Cutter et al. 2003; Ch. 25: Coastal Zone).

The California state government, through its Ocean and Coastal Resources Adaptation Strategy, along with local governments, is using new sea level mapping and information about social vulnerability to undertake coastal adaptation planning.

Heat Threats to Health

Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in Southwestern cities, which are home to more than 90 percent of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.

The Southwest has the highest percentage of its population living in cities of any U.S. region. Its urban population rate, 92.7%, is 12% greater than the national average (U.S. Census Bureau 2012). Increasing metropolitan populations already pose challenges to providing adequate domestic water supplies, and the combination of increased population growth and projected increased risks to surface water supplies will add further challenges (California Department of Water Resources 2009; Gleick 2010; Ray et al. 2008). Trade-offs are inevitable between conserving water to help meet the demands of an increasing population, and providing adequate water for urban greenery to reduce increasing urban temperatures.

Urban infrastructures are especially vulnerable because of their interdependencies; strains in one system can cause disruptions in another (Min et al. 2007; NRC 2002; Rinaldi et al. 2001). For example, an 11-minute power system disturbance in September 2011 cascaded into outages that left 1.5 million San Diego residents without power for 12 hours (Federal Energy Regulatory Commission and North American Electric Reliability Corporation 2012); the outage disrupted pumps and water service, causing 1.9 million gallons of sewage to spill near beaches (Medina 2011). Extensive use of air conditioning to deal with high temperatures can quickly increase electricity demand and trigger cascading energy system failures, resulting in blackouts or brownouts (Hayhoe et al. 2010; Mazur and Metcalfe 2012; Miller et al. 2008).

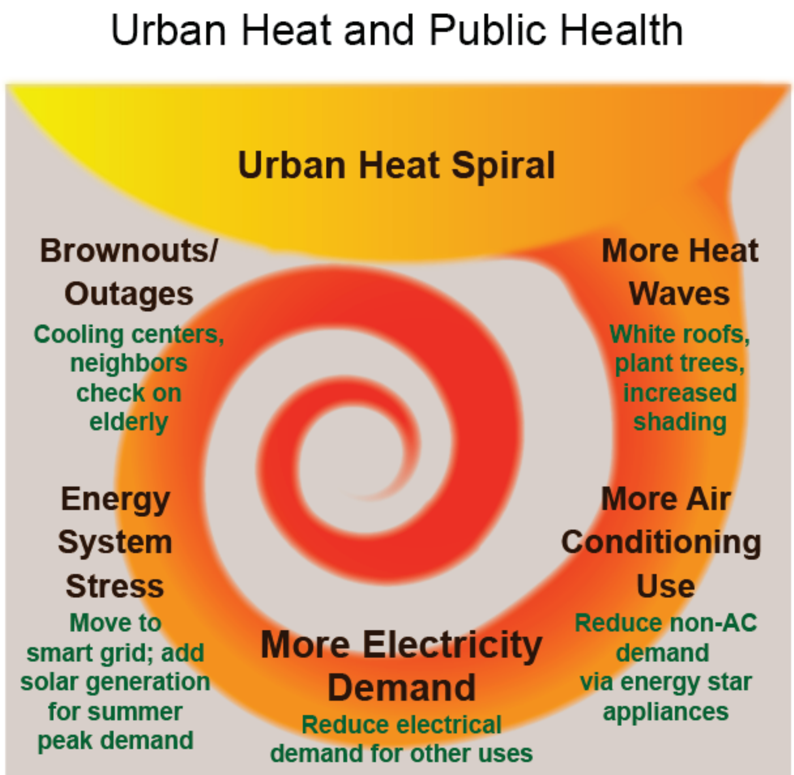


Figure 20.6: Urban Heat and Public Health

Caption: Description of a "vicious spiral" of warming in Southwest cities that could lead to serious increases in illness and death due to heat stress. This spiral shows how more heat waves can lead to increased occurrence of electric power brownouts and outages, which in turn reduce the availability of life-saving air conditioning. Shown in green above are various response options, such as increased use of more efficient architectural practices, more reflective building and paving materials, low water-use landscaping for shading, alternative energy, smart electric grid technologies, and improved public awareness, which can reduce vulnerability.

Heat stress, a recurrent health problem for urban residents, has been the leading weather-related cause of death in the United States since 1986 when record keeping began (NWS 2012) – and the highest rates nationally are found in Arizona (Brown et al. 2012). The effects of heat stress are greatest during heat waves lasting several days or more, and heat waves are projected to increase in frequency, duration, and intensity (Gershunov et al. 2009; Sheridan et al. 2011), become more humid (Gershunov et al. 2009), and cause a greater number of deaths (Ostro et al. 2011). Already, severe heat waves, such as the 2006 ten-day California event, have resulted in high mortality, especially among elderly populations (Ostro et al. 2009). In addition, evidence indicates a greater likelihood of impacts in less affluent neighborhoods, which typically lack shade trees and other greenery (Grossman-Clarke et al. 2010; Harlan et al. 2006; Pincetl et al. 2012).

Exposure to excessive heat can also aggravate existing human health conditions, like for those who suffer from respiratory or heart disease. Increased temperatures can reduce air quality, because atmospheric chemical reactions proceed faster in warmer conditions. The upshot is that heat waves are often accompanied by increased ground-level ozone, which can cause respiratory distress (Brown et al. 2012). Increased temperatures and longer warm seasons will also lead to shifts in the distribution of disease-transmitting mosquitoes (Brown et al. 2012).

Traceable Accounts

Chapter 20: Southwest

Key Message Process: A central component of the assessment process was the Southwest Regional Climate assessment workshop that was held in August 1-4, 2011 in Denver, CO with more than 80 participants in a series of scoping presentations and workshops that began the process leading to a foundational TIR report (Garfin et al. 2012). The report consists of nearly 800 pages organized into 20 chapters that were assembled by 122 authors representing a wide range of inputs including governmental agencies, NGOs, tribes, and other entities. The report findings were described in a townhall meeting at the American Geophysical Union meeting in 2011, and feedback collected and incorporated into the draft.

The chapter author team engaged in multiple technical discussions via over 15 biweekly teleconferences that permitted a careful review of the foundational TIR (Garfin et al. 2012) and of approximately 125 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team then met at the University of Southern California on 27-28 March, 2012 for expert deliberation of draft key messages by the authors, wherein each message was defended before the entire author team before this key message was selected for inclusion in the Report; these discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities".

Key message #1/5	**Snowpack and streamflow amounts are projected to decline, decreasing water supply for cities, agriculture, and ecosystems.**
Description of evidence base	The key message was chosen based on input from the extensive evidence documented in the SW Technical Input (Garfin et al. 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Key Message 5 in Chapter 2, Our Changing Climate, also provides evidence for declining precipitation across the U.S., and Kunkel et al. (2012) discuss regional outlooks and trends for the Southwest. Historical changes over the past 50 years have shown a reduction in the amount of snow in the total annual precipitation and the associated streamflow timing of snowfed rivers (Hidalgo et al. 2009; Pierce et al. 2008). For the "recent decade" (i.e., 2001-2010), snowpack evidence is from USDA-NRCS snow course data, updated through 2010. Streamflow amounts are for the four major river basins in the region, the Colorado, Sacramento-San Joaquin, Great Basin (Humboldt River, NV), and the Rio Grande; data are from Reclamation, California Department of Water Resources, USGS, and International Boundary and Water Commission (U.S. Section), respectively as analyzed by Hoerling et al. (2012). These data are backed by a rigorous detection and attribution study conducted by Barnett et al. (2008). Projected trends are from Cayan et al. (2012), and make use of downscaled climate parameters for 16 GCMs, and hydrologic projections for the Colorado River, Rio Grande and Sacramento-San Joaquin River System. When combined with temperature projections, there are likely reductions in spring snow accumulation and water supply for much of the Southwest, with enhanced impacts occurring in later time periods (Cayan et al. 2008; Cayan et al. 2010; Christensen and Lettenmaier 2007). Future flows in major Southwest rivers will decline as a result of a combination of increased temperatures, increased evaporation, less snow and less persistent

	snowpack. These changes have been projected to result in decreased surface water supplies, which will have impacts for allocation of water resources to major uses, such as urban drinking water, agriculture and ecosystem flows.
New information and remaining uncertainties	Uncertainty in climate change warming and precipitation response due to differences between GCMs, regional downscaling, uncertainty in hydrological modeling, and differences in emissions, aerosols, and other forcings, and internal climate variation produces different levels of snow loss in different model simulations. In addition to the aforementioned uncertainties pertaining to projection of regional climate and hydrology, projection of future water supply includes at least the following additional uncertainties: a) changes in water management, which depend on agency resources and leadership and cooperation of review boards and the public; b) management responses to non-stationarity; c) legal, economic, and institutional options for augmenting existing water supplies, adding underground water storage and recovery infrastructure, and fostering further water conservation; d) adjudication of unresolved water rights; e) local, state, regional and national policies related to the balance of agricultural, ecosystem and urban water use.
Assessment of confidence based on evidence	There is **high** confidence in the continued trend of declining snowpack and streamflow given the evidence base and remaining uncertainties. For the impacts on water supply, there is **high** confidence that reduced water supply will affect the region.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 20: Southwest

Key Message Process: See key message #1.

Key message #2/5	**The Southwest produces more than half the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increased temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.**
Description of evidence base	Increased competition for scarce water was presented in the first key message, and in Garfin et al (2012). Evidence of increased temperatures is brought out in the Urban impacts key message, and in Chapter 2: Our Changing Climate, Key Message 3 for the Nation. Chapter 2 also discusses extremes of moisture, cold and heat (Key Message 7). Kunkel et al. (2012) discusses the outlooks and trends both variables in the Southwest. There is abundant evidence of **irrigation dependence and vulnerability of high value specialty crops to extremes of moisture, cold, and heat**, including, prominently, the 2009 National Climate Assessment and Garfin et al. (2012). Southwest agricultural production statistics and irrigation dependence of that production is delineated in the USDA 2007 Census of Agriculture, the USDA Watersheds study (derived from the Census) and the USDA Farm and Ranch Irrigation Survey (FRIS). **Reduced Yields.** Even under the most conservative emission scenarios evaluated, Luedeling et al (2011) found that required winter chill periods are projected to fall below the hours that are necessary for many of the nut and fruit bearing trees of California, and yields are projected to decline as a result. Also Jackson et al. (2012a) found that California wheat acreage and walnut acreage will decline, due to increased temperatures. Drought and extreme weather are more likely to affect the market value of fruit and vegetables, as opposed to other crops, because they have high water content and because consumers expect good visual appearance and flavor (Hatfield et al. 2008). Extreme daytime and nighttime temperatures have been shown to accelerate crop ripening and maturity, reduce yield of crops such as corn, fruit trees, and vineyards, cause livestock to be stressed, and increase water consumption in agriculture (Battisti and Naylor 2009). **Irrigation water transfers to urban.** Warmer, drier future scenarios portend large transfers of irrigation water to urban areas even though agriculture will need additional water to meet crop demands, impacting local agriculturally dependent economies (Medellín-Azuara et al. 2012). In particular areas of the Southwest (most notably lower-central Arizona), a significant reduction in irrigated agriculture is already underway as land conversion occurs near urban centers (Pritchett et al. 2011). Functioning water markets, which may require legal and institutional changes, can enable such transfers, and reduce the social and economic impacts of water shortages to urban areas (Frisvold et al. 2012). The economic impacts of climate change on Southwest fruit and nut growers are likely to be substantial and will result in a northward shift for production of these crops, displacing growers and impacting communities.
New information and remaining uncertainties	Competition for water. The extent to which water transfers take place depends on whether complementary investments in conveyance or storage infrastructure are made. Currently, there are legal and institutional restrictions limiting water transfers across state and local jurisdictions. It is uncertain whether infrastructure investments will be made or institutional innovations facilitating transfers will

	develop. Institutional barriers will be greater if negative 3rd-party effects of transfers are not adequately addressed. Research to improve information base include (a) estimates of 3rd party impacts, (b) assessment of institutional mechanisms to reduce those impacts, (c) environmental impacts of water infrastructure projects, and (d) options and costs of mitigating those environmental impacts, would inform future water transfer debates. **Extremes and phenology.** A key uncertainty is the timing of the extreme events during the phenological stage of the plant or the growth cycle of the animal. For example, plants are more sensitive to extreme high temperatures and drought during the pollination stage compared to vegetative growth stages. **Genetic improvement potential.** Crop and livestock reduction studies by necessity depend on assumptions about adaptive actions by farmers and ranchers, however, agriculture has proven to be highly adaptive in the past. In particular, the ability of conventional breeding and biotechnology to keep pace with crop plant and animal genetic improvement needed for adaptation to climate induced biotic and abiotic stresses is highly uncertain.
Assessment of confidence based on evidence	Although evidence includes studies of observed climate and weather impacts on agriculture, projections of future changes using climate and crop yield models and econometric models show varying results, depending on the choice of crop and assumptions regarding water availability. Because net reductions in the costs of water shortages depend on multiple institutional responses, it is difficult as yet to locate a best-estimate water transfers between zero and the upper bound. Water scarcity may also be a function of trade-offs between economic returns for agricultural production versus returns for selling off property or selling water to urban areas (for example, Imperial Valley transfers to San Diego). Therefore confidence is **high** in this key message.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 20: Southwest

Key Message Process: See key message #1.

Key Message #3/5	**Increased warming, due to climate change, and drought have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.**
Description of evidence base	Increased warming and drought are extensively described in Garfin et al. (2012). Evidence of increased temperatures is brought out in Chapter 2: Our Changing Climate, Key Message 3 for the Nation. Chapter 2 also discusses extremes of moisture, cold and heat (Key Message #7). Kunkel et al. (2012) discusses the outlooks and trends both variables in the Southwest. Analyses of weather station data from the Southwest have detected changes from 1950 to 2005 that favor wildfire, and statistical analyses have attributed the changes to anthropogenic climate change. The changes include increased temperatures (Bonfils et al. 2008) , reduced snowpack (Pierce et al. 2008), earlier spring warmth (Ault et al. 2011) and streamflow (Barnett et al. 2008). These climate changes have increased background tree mortality rates from 1955 to 2007 in old-growth conifer forests in California, Colorado, Utah, and the Northwest (Van Mantgem et al. 2009) and caused extensive piñon pine mortality in Arizona, Colorado, New Mexico, and Utah between 1989 and 2003 (Breshears et al. 2005). Climate factors have contributed to increases in wildfire in the 20th century. In mid-elevation conifer forests of the western U.S., increases in spring and summer temperatures, earlier snowmelt, and longer summers increased fire frequency 400% and burned area 650% from 1970 to 2003 (Westerling et al. 2006). Multivariate analysis of wildfire across the western U.S. from 1916 to 2003 indicates that climate was the dominant factor controlling burned area, even during periods of human fire suppression (Littell et al. 2009). Reconstruction of fires of the past 400 to 3000 years in the western U.S. (Marlon et al. 2012; Trouet et al. 2010) and in Yosemite and Sequoia National Parks, California (Swetnam 1993; Swetnam et al. 2009; Taylor and Scholl 2012) confirm that temperature and drought are the dominant factors explaining fire occurrence. Four different fire models project increases in fire frequency across extensive areas of the Southwest in the 21st century (Gonzalez et al. 2010; Krawchuk et al. 2009; Litschert et al. 2012; Westerling et al. 2012). Multivariate statistical generalized additive models (Krawchuk et al. 2009) project extensive increases across the Southwest, but the models project decreases when assuming that climate alters patterns of net primary productivity. Logistic regressions (Westerling et al. 2012) project increases across most of California, except for some southern parts of the state, with average fire frequency increasing 37-74%. Linear regression models project up to a doubling of burned area in the southern Rockies by 2070 under scenarios B1 or A2 (Litschert et al. 2012). The MC1 dynamic global vegetation model projects increases in fire frequencies on 40% of the area of the Southwest from 2000 to 2100 and decreases on 50% for IPCC emissions scenarios B1 and A2 (Gonzalez et al. 2010). Excessive wildfire destroys homes, exposes slopes to erosion and landslides, and threatens public health, causing economic damage (Frisvold et al. 2011; Morton and Global Institute of Sustainable Forestry 2003; Richardson et al. 2011; WFLC 2010). Further impacts to communities and various economies (local, state, national) have been projected (Westerling et al. 2012).

New information and remaining uncertainties	Uncertainties in future projections derive from the inability of models to accurately simulate all past fire patterns, and the different General Circulation Models (GCMs), emissions scenarios, and spatial resolutions used by different fire model projections. Fire projections depend highly on the spatial and temporal distributions of precipitation projections, which vary widely across GCMs. Although models generally project future increases in wildfire, uncertainty remains on the exact locations. Research groups continue to refine the fire models.
Assessment of confidence based on evidence	There is **high** confidence in this key message given the extensive evidence base and discussed uncertainties.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 20: Southwest

Key Message Process: See key message #1.

Key message #4/5	**Flooding and erosion in coastal areas is already occurring and is damaging some areas of the California coast during storms and extreme high tides. Sea level rise is projected to increase, resulting in major damage as wind-driven waves ride upon higher seas and reach further inland.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the Technical Input (Garfin et al. 2012). Evidence for sea level rise across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Message 9) and its Traceable Accounts. All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. In addition, numerous recent studies (NRC 2012; Parris et al. 2012) produce much higher sea level-rise projections than what the IPCC reported in 2007 (IPCC 2007) for the rest of this century.
New information and remaining uncertainties	New information: There is strong recent evidence from satellite's such as GRACE, and from direct observations, that glaciers and ice caps worldwide are losing mass faster than expected, accounting for the recent increase in the rate of sea level rise that was not accounted for from temperature increase alone. Major uncertainties are associated with sea level rise projections such as the behavior of ice sheets with global warming and the actual level of global warming that the Earth will experience in the future (NRC 2012; Parris et al. 2012). The NRC report indicates that regional sea level rise projections are even more uncertain than the projections for global averages because local factors such as the steric (changes in the volume of water with changes in temperature and salinity) component of sea level-rise at regional levels and the vertical movement of land have large uncertainties (NRC 2012). However, it is virtually certain that sea levels will go up with a warming planet as demonstrated in the paleoclimatic record, modeling, and from basic physical arguments.
Assessment of confidence based on evidence	Given the evidence, especially since the last IPCC report, there is **high** confidence the sea level will continue to rise and that this will entail major damage to coastal regions.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 20: Southwest

Key Message Process: See key message #1.

Key message #5/5	Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in Southwestern cities, which are home to more than 90 percent of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.
Description of evidence base	There is excellent agreement regarding urban heat islands and exacerbation of heat island temperatures by climate change-caused increases in regional temperatures. There is abundant evidence of urban heat island effect for some Southwest cities (e.g., Sheridan et al. 2011), as well as several studies, some from outside the region, of the public health threats of urban heat to residents (e.g., Ostro et al. 2011; Ostro et al. 2009). Evidence includes observed urban heat island studies and modeling of future climates, including some climate change modeling studies for individual urban areas (e.g., Phoenix, Los Angeles). There is wide agreement in Southwest states that increasing temperatures combined with projected population growth will stress urban water supplies and require continued water conservation and investment in new water supply options. There is substantial agreement that disruption to urban electricity can cause cascading impacts, such as loss of water, and that projected diminished supplies will pose challenges for urban cooling (i.e., need for supplemental irrigation for vegetation-based cooling). However, there are no studies on urban power disruption induced by climate change and the emerging studies on power blackouts since 1984 do not identify high temperatures/heatwaves as a separate cause triggering blackouts. With projected surface water losses, and increasing water demand due to increasing temperatures and population, water supply in Southwest cities will require greater conservation efforts and capital investment in new water supply sources (Gleick 2010). Several Southwestern states, including California, New Mexico and Colorado have begun to study climate impacts to water resources, including impacts in urban areas (Ray et al. 2008; California Department of Water Resources 2009). The interdependence of infrastructure systems, especially the dependence of systems on electricity and communications and control infrastructures, and the potential cascading effects of breakdowns in infrastructure systems are well established (Min et al. 2007; NRC 2002). The concentration of infrastructures in urban areas adds to the vulnerability of urban populations to infrastructure breakdowns. This has been documented in descriptions of major power outages such as the Northeast Power Blackout of 2003, or the recent September 2011 San Diego blackout (Federal Energy Regulatory Commission and North American Electric Reliability Corporation 2012). A few references point to the role of urban power outages in threatening public health (loss of air conditioning) (Hayhoe et al. 2010; Miller et al. 2008)and water supplies (Federal Energy Regulatory Commission and North American Electric Reliability Corporation 2012).
New information and remaining uncertainties	Key uncertainties include the intensity and spatial extent of drought/heat waves. Uncertainty is associated with quantification of the impact of temperature and water availability on energy generation, transmission, distribution, and consumption – which have an impact on possible disruptions to urban electricity. Major disruptions are contingent on a lack of operator response and/or adaptive

	actions.
Assessment of confidence based on evidence	The urban heat island effect is well demonstrated and hence projected climate-induced increases to heat will increase exposure to heat-related illness. Disruptions are a key uncertain factor. Based on the substantial evidence and the remaining uncertainties, confidence in each aspect of the key message is **high**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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21. Northwest

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Key Messages

1. **Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.**
2. **In the coastal zone, the effects of erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.**
3. **The combined impact of increasing wildfire, insect outbreaks, and diseases is virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Almost complete loss of subalpine forests is expected by the 2080s.**
4. **While the agriculture sector's technical ability to adapt to changing conditions can offset some of the adverse impacts of a changing climate, there remain critical sector-specific concerns with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.**

Introduction

With craggy shorelines, volcanic mountains, and high sage deserts, the Northwest's complex and varied topography contributes to the region's rich climatic, geographic, social, and ecologic diversity. Abundant natural resources – timber, fisheries, productive soils, and plentiful water – remain important to the region's economy.

Snow accumulates in mountains, melting in spring to power both the region's rivers and economy, creating enough hydropower (40% of national total) (NWPCC 2010) to export 2 to 6 million megawatt hours/month (EIA 2011). Snowmelt waters crops in the dry interior, helping the region produce tree fruit (#1 in the world) and almost $17 billion worth of agricultural commodities including 55%, 15%, and 11% of U.S. potato, wheat, and milk production respectively (USDA 2012a, 2012b).

Seasonal water patterns shape the region's flora and fauna, including iconic salmon and steelhead, and forested ecosystems, which cover 47% of the landscape (Smith et al. 2009). Along more than 4,400 miles of coastline, regional economic centers are juxtaposed with diverse habitats and ecosystems that support thousands of species of fish and wildlife, including commercial fish and shellfish resources valued at $480 million in 2011 (NOAA 2012).

Adding to the influence of climate, human activities have altered natural habitats, threatened species, and extracted water to the limits in dry years. More recently, efforts have multiplied to balance environmental restoration and economic growth while evaluating climate risks. As conflicts and trade-offs increase, the region's population continues to grow – and the regional consequences of climate change continue to unfold. The need to seek solutions to these conflicts is becoming increasingly urgent.

Observed Climate Change

Temperatures have increased across the region over the past century, with a regionally averaged warming of about 1.5°F (Kunkel et al. 2012; Mote 2003). Trends in precipitation have varied among locations, seasons, and time periods of analysis, but precipitation has generally increased, especially in spring. Studies of extreme precipitation use different time periods and definitions of extreme, but most conclude that extreme precipitation (heavy downpours) increased somewhat in the Northwest, as in the rest of the country (Groisman et al. 2004; Madsen and Figdor 2007; Rosenberg et al. 2010). These and other climate trends include as yet unquantified contributions from both human influences (chiefly heat-trapping or "greenhouse" gases) and natural climate variability, and the trends are consistent with expected changes from human activities (Ch 2: Our Changing Climate, Key Message 1). Additional aspects of observed climate change in the region appear under the key messages below.

Projected Climate Change

Over the period from 1970-99 to 2070-99, an increase in average annual temperature of 3.3°F to 9.7°F is projected, depending largely on whether global emissions eventually decline (B1 scenario) or continue to rise (A1B, A2 scenarios), and is projected to be largest in summer. Change in annual average precipitation, averaged over the Northwest, is projected to be within a range of –11% to +12% for the B1, A1B, and A2 scenarios for 2030-2059 and –10% to +18% for 2070-99 (Mote and Salathe 2010). Seasonally, model projections range from modest decreases to large increases in winter, spring, and fall (Kunkel et al. 2012; Mote and Salathé 2010; Ch. 2: Our Changing Climate; Key Message 5). Projections of precipitation are less certain than those for temperature (Kunkel et al. 2012), yet one aspect of seasonal changes in precipitation is largely consistent across climate models: for scenarios of continued growth in global emissions, summer precipitation is projected to decrease by as much as 30% by the end of the century (Kunkel et al. 2012; Mote and Salathé 2010). Although Northwest summers are already dry, so that a 10% reduction is a small amount of precipitation, unusually dry summers have many noticeable consequences, including low streamflow west of the Cascades (Bumbaco and Mote 2010) and greater extent of wildfires throughout the region (Littell et al. 2010).

Ongoing research on the implications of these changes largely confirms projections and analyses made over the last decade while providing more information about how climate impacts are likely to vary from place to place within the region. In addition, new areas of concern like ocean acidification have arisen.

Water-related Challenges

Changes in the timing of streamflow related to changing snowmelt have been observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of observed and projected changes

Observed regional warming has been linked to hydrologic changes in basins with significant snowmelt contributions to streamflow. Since around 1950, area-averaged spring snowpack decreased 0% to 30% (depending on method and period of analysis) (Mote 2006; Pierce et al. 2008), spring snowmelt occurred 0 to 30 days earlier (Stewart et al. 2005), late winter/early spring streamflow increased (Hidalgo et al. 2009) and summer flow decreased 0% to 15% as a fraction of annual total flow (Luce and Holden 2009; Stewart et al. 2005), and winter flow increased, (U.S. Bureau of Reclamation 2011a) with exceptions in smaller areas and shorter time periods (Mote et al. 2008a).

Observed Shifts in Streamflow Timing

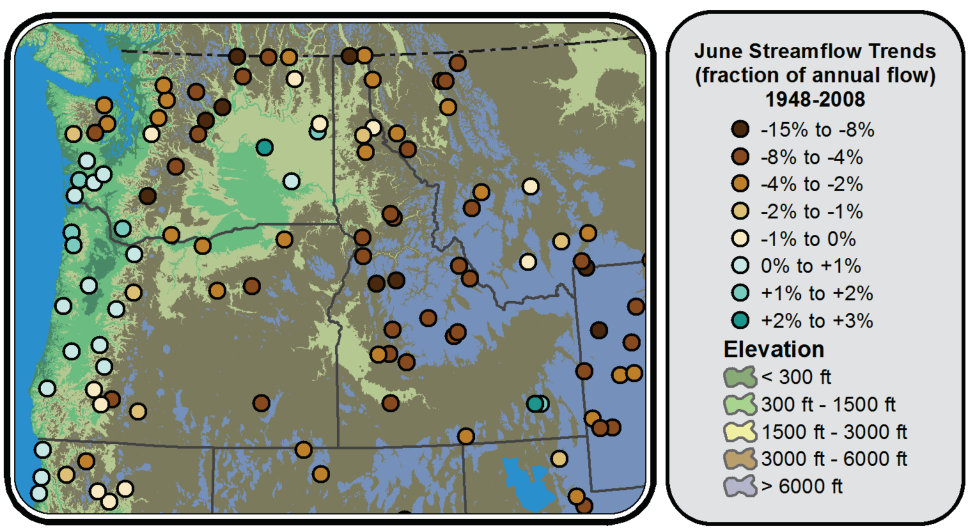
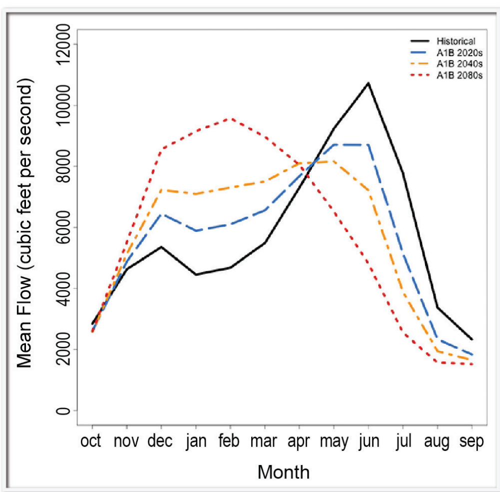


Figure 21.1: Observed Shifts in Streamflow Timing

Caption: Reduced June flows in many Northwest snow-fed rivers is a signature of warming in basins with a significant snowmelt contribution. The fraction of annual flow arriving in June increased slightly in rain-dominated coastal basins and decreased in mixed rain-snow basins and snowmelt dominated basins for 1948-2008 (Fritze et al. 2011). June is during the high flow period for most Northwest river basins; decreases in summer flows can make it more difficult to meet a variety of competing human and natural demands for water.

Hydrologic response to climate change varies by type of watershed, with the largest responses in basins with significant snow accumulation, where warming increases winter flows and advances the timing of spring melt (Hamlet and Lettenmaier 2005; Hidalgo et al. 2009). By 2050, snowmelt is projected to shift 3 to 4 weeks earlier than the 20th century average (Barnett et al. 2005; U.S. Bureau of Reclamation 2008), and summer flows are projected to be substantially lower (Elsner et al. 2010). Change in flood risk depends on many factors, but is projected to increase the most in mixed basins (those with both winter rainfall and summer snowmelt-related runoff peaks) and decrease in higher basins (Hamlet and Lettenmaier 2007; Mantua et al. 2010). Regional climate models project increases of 0% to 20% in extreme daily precipitation depending on location and definition of "extreme" (for example, annual wettest day), with a 13% regionally averaged increase in number of days with over one inch of precipitation for 2041-2070 compared with 1971-2000 (Kunkel et al. 2012). This increase in heavy downpours could increase future flood risk in transient and rain-dominant basins.



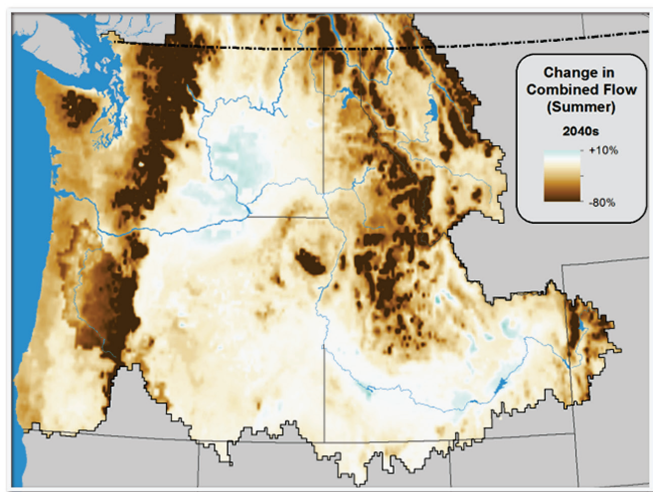


Figure 21.2 (left): Future Shift in Timing of Stream Flows

Left caption: Projected increased winter flows and decreased summer flows in many Northwest rivers will cause widespread impacts. Mixed rain-snow watersheds, such as the Yakima River basin, an important agricultural area in eastern Washington, will see increased winter flows, earlier spring peak flows, and decreased summer flows in a warming climate. Changes in average monthly stream flow from baseline (simulated 1916-2006 average, black) to the 2020s (blue), 2040s (yellow), and 2080s (red) indicate that the Yakima could change from a basin deriving most of its streamflow from snow melt to a rain-dominant basin by the 2080s under a scenario that assumes continued increases in emissions through mid century but declines thereafter (A1B) (Elsner et al. 2010).

Figure 21.2 (right): Reduced Summer Flows

Right caption: Across most of the Northwest, flows during the already low summer flow period would be significantly reduced in the 2040s compared to baseline (1915-2006) conditions under the same scenario (A1B) (Littell et al. 2011). This would put stress on freshwater fish species such as endangered salmon and bull trout and necessitate increasing trade-offs among conflicting users of summer water.

Consequences and likelihoods of changes

Reservoir systems have multiple objectives, including irrigation, municipal and industrial use, hydropower production, flood control, and preserving fish habitat. Modeling studies indicate, with near 100% likelihood, that reductions in summer flow will occur by 2050 in basins with significant snowmelt (Elsner et al. 2010). Combined with summer increases in heat-driven electric power demand for cooling (Hamlet et al. 2010) and evaporative demand from crops and forests (Kunkel et al. 2012; U.S. Bureau of Reclamation 2011b), these reduced flows will require tradeoffs among objectives of the whole system of reservoirs (Isaak et al. 2011). For example, reductions in hydropower production of as much as 20% by the 2080s could be required to preserve in-stream flow targets for fish in the Columbia River basin (Payne et al. 2004). Springtime irrigation diversions increased between 1970 and 2007 in the Snake River basin, as earlier snowmelt led to reduced spring soil moisture (Hoekema and Sridhar 2011). In the absence of adaptation, annual hydropower production is much more likely to decrease than to increase; economic impacts of hydropower changes could be substantial, on the order of hundreds of millions of dollars per year (Markoff and Cullen 2008).

Several aspects of hydrologic change, such as increased flooding in mixed rain-snow basins, region-wide increased winter flows and summer temperatures, and decreased summer flows, will threaten many freshwater species, particularly salmon, steelhead, and trout. Rising temperatures will increase disease and/or mortality in several iconic salmon species, including spring/summer Chinook and sockeye, especially in the interior Columbia and Snake River basins (Mantua et al. 2010) – although some streams are less sensitive to warming because of the temperature buffering provided by snowmelt and groundwater (Mohseni et al. 1999). By the 2080s, suitable habitat for the four trout species of the interior western U.S. is projected to decline 47% on average compared to 1978-97 (Wenger et al. 2011). Some Northwest streams (Isaak et al. 2011) and lakes have already warmed, on average, over the past three decades, contributing to changes such as earlier Columbia River sockeye salmon migration (Crozier et al. 2011) and earlier blooms of algae in Lake Washington (Winder and Schindler 2004). As species respond to climate change in diverse ways, there is a potential for ecological mismatches to occur – such as in the timing of the emergence of predators and their prey (Winder and Schindler 2004).

Adaptive capacity and implications for vulnerability

The ability to adapt to climate changes is strengthened by extensive water resources infrastructure, diversity of institutional arrangements (Slaughter et al. 2010), and management agencies that are responsive to scientific input. However, overallocation of existing water supply, conflicting objectives, limited management flexibility caused by rigid water allocation and operating rules, and other institutional barriers to changing operations continue to limit progress towards adaptation in many parts of the Columbia River basin (Hamlet 2011; Miles et al. 2000).

Vulnerability is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated, mid-elevation, temperature-sensitive, mixed rain-snow watersheds with existing conflicts among users of summer water. Regional power planners have expressed concerns over the existing hydroelectric system's potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints (NWPCC 2010). In contrast, vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins), and where institutional arrangements are simple, and current natural and human demands rarely exceed current water availability (EPA 2010; Hamlet 2011; King County Department of Natural Resources and Parks 2009; Palmer and Hahn 2002; Vano et al. 2010b).

The adaptive capacity of freshwater ecosystems also varies and, in managed basins, will depend on the degree to which the need to maintain streamflows and water quality for fish and wildlife is balanced with human uses of water resources. In highly managed rivers, release of deeper, colder water from reservoirs could offer one of the few direct strategies to lower water temperatures downstream (Yates et al. 2008). Actions to improve stream habitat, including planting trees for shade, are being tested. In more natural streams, some species may be able to change behavior or take advantage of cold-water refugia (Goniea et al. 2006; High et al. 2006).

Coastal Vulnerabilities

In the coastal zone, the effects of erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

With diverse landforms (beaches, rocky shorelines, bluffs, estuaries), coastal and marine ecosystems, and human uses (rural communities, dense urban areas, international ports, transportation), the Northwest coast will experience a wide range of climate impacts.

Description of observed and projected changes

Along much of the coast in the Northwest, tectonic uplift reduces apparent sea level rise below the currently observed global average, though a major earthquake in the subduction zone, expected within the next few hundred years, would immediately reverse centuries of uplift and increase relative sea level about 40 inches or more (Atwater and Yamaguchi 1991; NRC 2012). Global sea levels have risen 8 inches since 1880 and are projected to rise another 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 9). Many local factors can modify the global trend, including vertical land movement, oceanic circulation and local effects of ice loss in southeast Alaska, sediment compaction, subterranean fluid withdrawal (groundwater, natural gas), and other geophysical factors. Taking into account all of these factors and considering a wider range of emissions scenarios than are used in this assessment, a recent evaluation focused on the west coast calculated projected sea level rise and ranges for specific sites in the Northwest by 2100, relative to 2000 (NRC 2012). This type of evaluation can provide local decision-makers with the most relevant information specific to their coastline. In addition to the range of sea level rise projected for specific locations within the Northwest, El Niño conditions alone could temporarily increase sea level by about 4 to 12 inches across the region (NRC 2012).

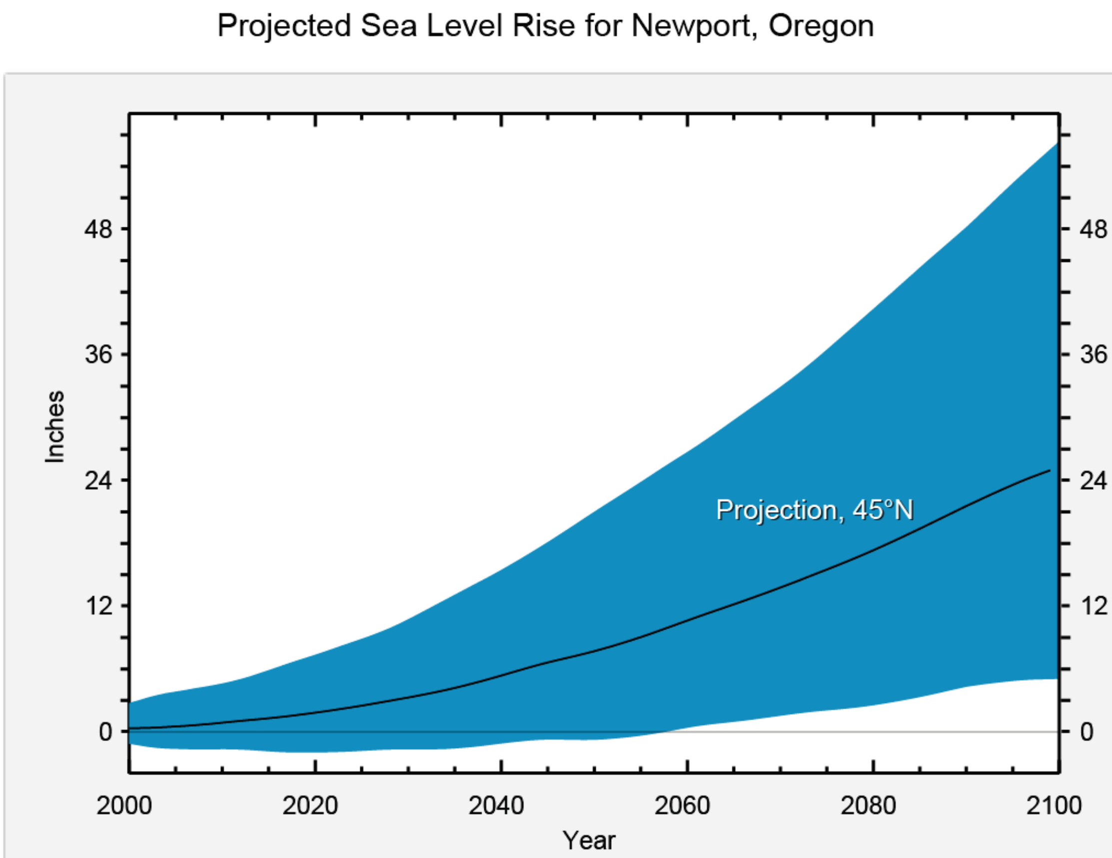


Figure 21.3: Projected Sea Level Rise for Newport, OR

Caption: Projected sea level rise for Newport, OR (in inches relative to the year 2000) is based (NRC 2012) on a broader suite of emissions scenarios (B1-A1F1) and a more detailed calculation than in this assessment (See Ch. 2: Our Changing Climate). The blue area shows the range of sea level rise and the black line shows the projection based on the methodology used in the NRC report, which incorporates global and local effects of warming oceans, melting land ice, and vertical land movements. Given the impossibility of assigning likelihood to any one possible trajectory of sea level rise at this time, a reasonable risk assessment for local adaptation planning would consider multiple scenarios within the full range of possible outcomes. (Source: Plotted with data from NRC 2012).

Northwest coastal waters, some of the most productive on the West Coast (Hickey and Banas 2008), have highly variable physical and ecological conditions as a result of seasonal and inter-annual (year-to-year) changes in upwelling of deeper marine water that make changes over time difficult to detect. Coastal sea surface temperatures have been shown to have increased since the 1900s (Deser et al. 2010; Field et al. 2006), and summertime fog has declined, both of which could be consequences of weaker upwelling winds (Johnstone and Dawson 2010). Projected future changes include increasing but highly variable acidity (Butorac et al. 2010; Feely et al. 2008; Feely et al. 2010), increasing surface water temperature (2.2°F from 1970-99 to 2030-59) (Mote et al. 2010), and possibly changing storminess (Gemmrich et al. 2011; Ruggiero et al. 2010). Climate models show inconsistent projections for the future of Northwest coastal upwelling (Mote and Salathé 2010; Wang et al. 2010).

Consequences and likelihoods of changes

In Washington and Oregon, more than 140,000 acres of coastal lands lie within 3.3 feet in elevation of high tide (Strauss et al. 2012). As sea levels continue to rise, these areas will be inundated more frequently. Many coastal wetlands, tidal flats, and beaches will probably decline in quality and extent as a result of sea level rise, particularly where inland shifting of habitats is precluded. Species such as shorebirds and forage fish (small fish eaten by larger fish, birds, or mammals) would be harmed, and coastal infrastructure and communities would be at greater risk from coastal storms (Drut and Buchanan 2000; Krueger et al. 2010).

Ocean acidification threatens culturally and commercially significant marine species directly affected by changes in ocean chemistry (like oysters) and those affected by changes in the marine food web (like Pacific salmon) (Ries et al. 2009). Northwest coastal waters are among the most acidified worldwide, especially in spring and summer with coastal upwelling (Butorac et al. 2010; Feely et al. 2008; Hickey and Banas 2003; NOAA's Northwest Fisheries Science Center) combined with local factors in estuaries (Butorac et al. 2010; Feely et al. 2010).

Increasing coastal water temperatures and changing ecological conditions may alter the ranges, types, and abundances of marine species (Hollowed et al. 2001; Tillmann and Siemann 2011). Recent warm periods in the coastal ocean, for example, saw the arrival of subtropical and offshore marine species from zooplankton to top predators such as striped marlin, tuna, and yellowtail more common to the Baja area (Pearcy 2002; Peterson and Schwing 2003). Warmer water in Puget Sound may contribute to a higher incidence of harmful blooms of algae linked to neurotoxic shellfish poisoning (Feely et al. 2010; Huppert et al. 2009; Moore et al. 2008).

Many human uses of the coast – for living, working, and recreating – will also be negatively affected by the physical and ecological consequences of climate change. Erosion, inundation, and flooding will threaten: public and private property along the coast; infrastructure, including wastewater treatment plants (Solecki and Rosenzweig 2012); stormwater outfalls (Fleming and Rufo-Hill 2012; Haub 2012, personal communication); ferry terminals (WSDOT 2011); and coastal road and rail transportation, especially in Puget Sound (MacArthur et al. 2012). Municipalities from Seattle (Fleming and Rufo-Hill 2012) and Olympia (Haub 2012, personal communication), Washington, to Neskowin, Oregon, have mapped risks from the combined effects of sea level rise and other factors.

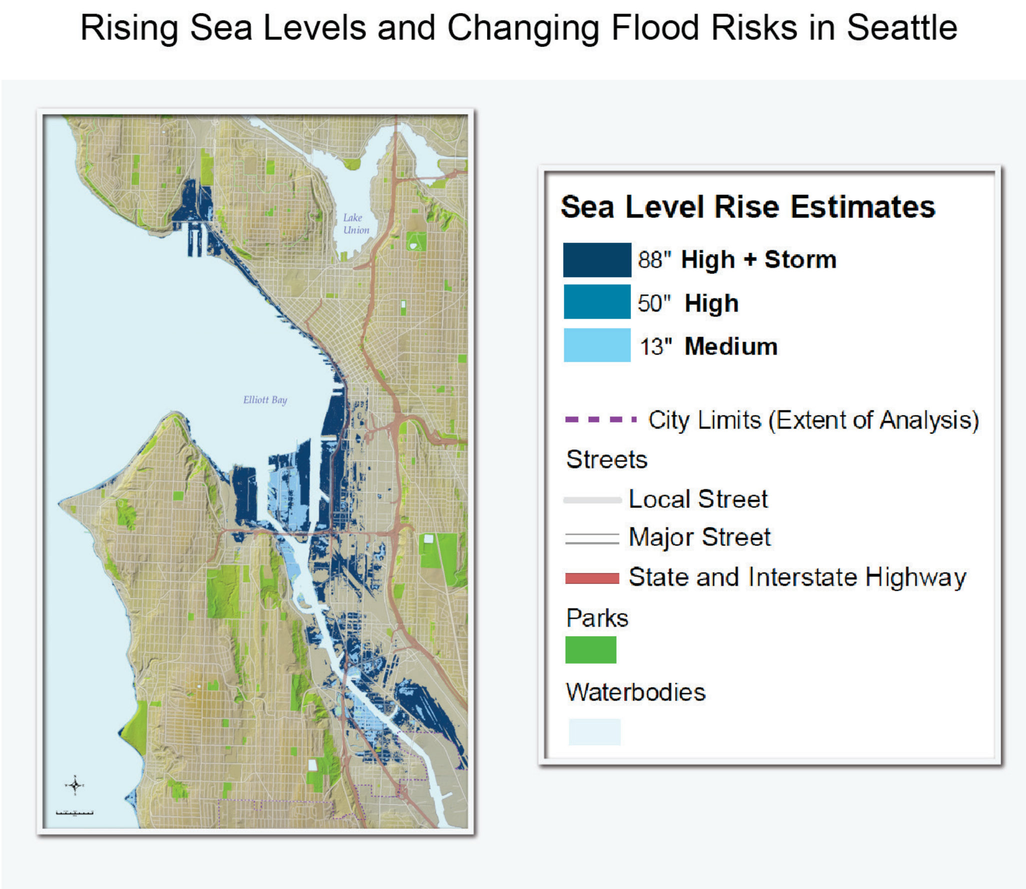


Figure 21.4: Rising Sea Levels and Changing Flood Risks in the City of Seattle

Caption: Areas of Seattle projected by Seattle Public Utilities to be below sea level during high tide (Mean Higher High Water) and therefore at risk of flooding or inundation are shaded in blue under three levels of sea level rise, (Mote et al. 2008b), assuming no adaptation (Fleming and Rufo-Hill 2012; Seattle Public Utilities 2010). (High [50 inches] and medium [13 inches] levels are within the range projected for the Northwest by 2100; the highest level incorporates the compounding effect of storm surge). Unconnected inland areas shown to be below sea level may not be inundated, but could experience problems due to areas of standing water caused by a rise in the water table and drainage pipes backed up with sea water. (Figure source: Courtesy of Seattle Public Utilities)

Adaptive capacity and implications for vulnerability

Human activities have increased the vulnerability of many coastal ecosystems, by degrading and eliminating habitat (Good 2000; WDNR 1998) and by building structures that, along with natural bluffs, thwart inland movement of many remaining habitats. In Puget Sound, for example, an estimated one-third of the shoreline has been modified by seawalls, bulkheads, and other structures (Fresh et al. 2011), though some restoration has occurred. Human response to erosion and sea level rise, especially shoreline armoring, will largely determine the viability of many shallow-water and estuarine ecosystems (Huppert et al. 2009; Puget Sound Nearshore Ecosystem Restoration Project 2011; Tillmann and Siemann 2011). In communities with few alternatives to existing coastal infrastructure, such as parts of Highway 101 in Oregon, sea level rise and storm surges will pose an increasing threat to local commerce and livelihoods. Finally, there seem to be few options for ameliorating projected ocean acidification (Washington Governor's Blue Ribbon Panel on Ocean Acidification 2012).

Figure 21.5: Adapting the Nisqually River Delta to Sea Level Rise

Caption: In the Nisqually River Delta in Washington, estuary restoration on a large scale to assist salmon and wildlife recovery provides an example of adaptation to climate change and sea level rise. After a century of isolation behind dikes (left), much of the Nisqually National Wildlife Refuge was reconnected in 2009 with tidal flow by removal of a major dike and restoration of 762 acres (right), with the assistance of Ducks Unlimited and the Nisqually Indian Tribe. This reconnected more than 21 miles of historical tidal channels and floodplains with Puget Sound (U.S. Fish and Wildlife Service 2010). A new exterior dike was constructed to protect freshwater wetland habitat for migratory birds from tidal inundation and future sea level rise. Combined with expansion of the authorized Refuge boundary, ongoing acquisition efforts to expand the Refuge will enhance the ability to provide diverse estuary and freshwater habitats despite rising sea level, increasing river floods, and loss of estuarine habitat elsewhere in Puget Sound. This project is considered a major step in increasing estuary habitat and recovering the greater Puget Sound estuary.

Figure credits/sources: Left (backhoe): Jesse Barham/U.S. Fish and Wildlife Service http://www.flickr.com/photos/usfwspacific/5791362738/in/set-72157626745822317); Right (aerial): Jean Takekawa/U.S. Fish and Wildlife Service (http://www.flickr.com/photos/usfwspacific/5790804083/in/set-72157626745822317)

Impacts on Forests

The combined impact of increasing wildfire, insect outbreaks, and diseases is virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Almost complete loss of subalpine forests is expected by the 2080s.

Evergreen coniferous forests are a prominent feature of Northwest landscapes, particularly in mountainous areas. Forests support diverse fish and wildlife species, promote clean air and water, stabilize soils, and store carbon. They support local economies and traditional tribal uses, and provide recreational opportunities.

Description of observed and projected changes
Climate change will alter Northwest forests by increasing wildfire risk, insect and disease outbreaks, and by forcing longer-term shifts in forest types and species. Many impacts will be driven by water deficits, which increase tree stress and mortality, tree vulnerability to insects, and fuel flammability. The cumulative effects of disturbance – and possibly interactions between insects and fires – will cause the greatest changes in Northwest forests (Littell et al. 2010; McKenzie et al. 2008). A similar outlook is expected for the Southeast region (See Ch. 20: Southeast, Key Message 3).

Although wildfires are a natural part of most Northwest forest ecosystems, warmer and drier conditions have helped increase the number and extent of wildfires in western U.S. forests since the 1970s (Littell et al. 2010; McKenzie et al. 2008; McKenzie et al. 2004; Westerling et al. 2006). This trend is expected to continue under future climate conditions. By the 2080s, the median annual area burned in the Northwest would quadruple relative to the 1916-2007 period to 2 million acres (range 0.2 to 9.8 million acres) under a scenario that assumes continued increases in emissions through mid century but declines thereafter (A1B). The probability of a very large fire year would increase from 1 in 20 to 1 in 2 (Littell et al. 2010).

Figure 21.6: Forest mortality

Caption: Forest mortality due to fire and insect activity is already evident in the Northwest, and continued changes in climate in coming decades are expected to increase these effects. Recent burn (left side of watershed) and trees killed by mountain pine beetle and spruce beetle infestations (right side of watershed) in subalpine forest in the Pasayten Wilderness, Okanogan Wenatchee National Forest, Washington. Figure source: Jeremy Littell, USGS.

Higher temperatures and drought stress are contributing to outbreaks of mountain pine beetle that increase pine mortality in drier Northwest forests (Carroll et al. 2003; Logan and Powell 2001; Oneil 2006). This trend is projected to continue with ongoing warming (Bentz et al. 2010; Hicke et al. 2006; Littell et al. 2010; Mitchell and Buffam 2001). The proportion of Northwest pine forests where mountain pine beetles are most likely to survive is projected to first increase (27% higher in 2001-2030 compared to 1971-2000) and then decrease (about 49% to 58% lower by 2071-2100) (Bentz et al. 2010). Between now and the end of this century, the elevation of suitable beetle habitat is projected to increase, exposing higher elevation forests to the pine beetle but ultimately limiting available area (Bentz et al. 2010; Hicke et al. 2006; Littell et al. 2010).

The areas most climatically suited for many tree species will shift from their current locations, increasing vulnerability to insects, disease, and fire in areas that become unsuitable. Eighty-five percent of the current range of three species that are host to pine beetles is projected to be climatically unsuitable for one or more of those species by the 2060s (Littell et al. 2010; Rehfeldt

2006), while 21 to 38 currently existing plant species may no longer find climatically appropriate habitat in the Northwest by late this century (McKenney et al. 2011).

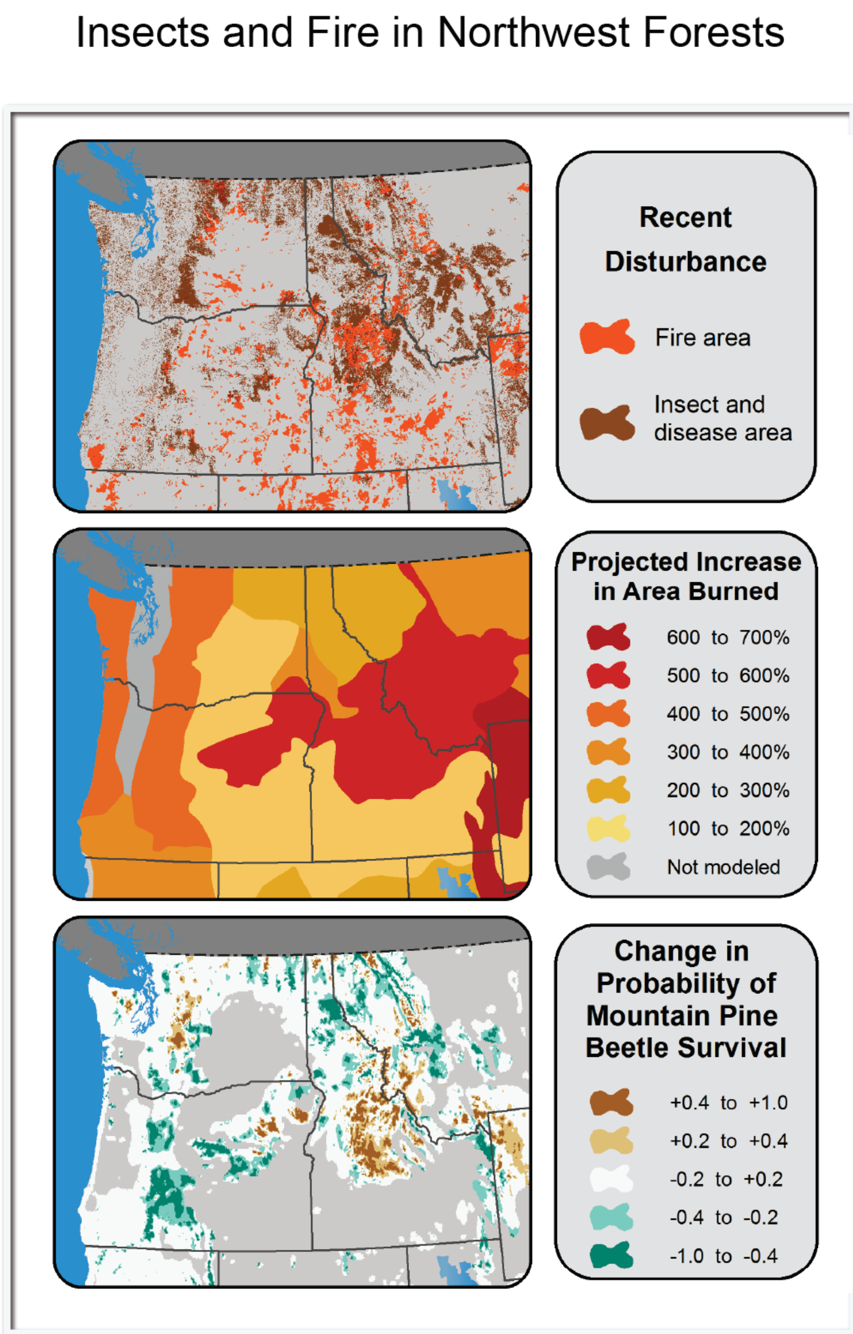


Figure 21.7: Insects and Fire in Northwest Forests

Caption Top: Insects and fire have cumulatively affected large areas of the Northwest, and are projected to be the dominant drivers of forest change in the near future. Map shows areas recently burned (1984-2008)(Eidenshink et al. 2007; USGS 2012) or affected by insects or disease (1997-2008) (USFS 2012).

Caption Middle: Large increases in area burned by wildfire are projected for most of the Northwest. Projected changes in area burned associated with a 2.2°F global warming, including both the expected temperature and precipitation changes (NRC 2011). The divisions are areas that share common climatic and vegetation characteristics (Bailey 1995).

Caption Bottom: Projected changes in the probability of mountain pine beetle climatic suitability for the period 2001-2030 relative to 1971-2000, where brown indicate areas where pine beetles are projected to increase in the future and green indicates areas where pine beetles are expected to decrease in the future. Changes in probability of survival are based on climate-dependent factors important in beetle population success, including cold tolerance (Régnière and Bentz 2007), spring precipitation (Safranyik et al. 1975), and seasonal heat accumulation (Bentz et al. 2010; Logan and Powell 2001).

Consequences and likelihoods of changes

The likelihoods of increased disturbance and altered forest distribution are very high in areas dominated by natural vegetation, and the resultant changes in habitat would affect native species and ecosystems. Subalpine forests and alpine ecosystems are especially at risk, and may undergo almost complete conversion to other vegetation types by the 2080s (Rogers et al. 2011). Changes in the risk of very large, high-intensity, stand-replacing fires cannot yet be predicted, but such events could have enormous impacts for forest dependent species (McKenzie et al. 2004). Increased wildfire could exacerbate respiratory and cardiovascular illnesses in nearby populations due to smoke and particulate pollution (Baron et al. 2008; Karl et al. 2009; Washington State Department Ecology 2012). The economic impacts of climate change in Northwest forests would be moderate for the region as a whole, but could significantly affect local timber revenues and bioenergy markets (Capalbo et al. 2010).

Adaptive capacity and implications for vulnerability

Ability to prepare for these changes varies with land ownership and management priorities. Adaptation actions that decrease forest vulnerability exist, but none is appropriate across all of the Northwest's diverse climate threats, land-use histories, and management objectives (Littell et al. 2012; Millar et al. 2007; Peterson et al. 2011). Surface and canopy thinning can reduce the occurrence and effects of high severity fire in previously low severity fire systems, like drier eastern Cascades forests (Peterson and Johnson 2007; Prichard et al. 2010), but may be ineffective in historically high severity fire forests, like the western Cascades, Olympics, and some subalpine forests. It is possible to use thinning to reduce tree mortality from insect outbreaks (Chmura et al. 2011; Littell et al. 2012), but not on the scale of the current outbreaks in much of the West.

Adapting Agriculture

While the agriculture sector's technical ability to adapt to changing conditions can offset some of the adverse impacts of a changing climate, there remain critical sector-specific concerns with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Agriculture provides the economic and cultural foundation for Northwest rural populations and contributes substantively to the overall economy. Agricultural commodities and food production systems contributed 3% and 11% of the region's GDP, respectively in 2009 (Brady and Taylor 2011; ODA 2009; U.S. Government Revenue 2012; USDA 2011a, 2011b, 2011c). Although the overall consequences of climate change will probably be lower in the Northwest than in certain other regions, sustainability of some Northwest agricultural sectors is threatened by soil erosion (Kok et al. 2009; Mulla 1986) and water supply uncertainty, both of which could be exacerbated by climate change.

Description of observed and projected changes

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, a specific range of temperatures, precipitation, and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming will reduce the availability of irrigation water in snowmelt-fed basins, as described above, and increase the probability of heat stress to field crops and tree fruit. Some crops will benefit from a longer growing season (Stöckle et al. 2010) and/or higher atmospheric CO_2, at least for a few decades (Hatfield et al. 2011; Stöckle et al. 2010). Longer-term consequences are less certain. Changes in plant diseases, pests, and weeds present additional risks but are species-specific, preventing general projections. In general, higher temperatures are coupled with greater pressure from insect pests, stemming from changes in geographic ranges and dates of spring arrival (Parmesan 2006; Trumble and Butler 2009).

Consequences of changes

Because much of the Northwest has low annual precipitation, many crops require irrigation. Reduction in summer flows in snow-fed rivers ("Reduced Summer Flows" figure above), coupled with warming that could increase agricultural and other demands, potentially produces irrigation water shortages (Washington State Department of Ecology 2011). The risk of a water-short year – when Yakima basin junior water rights holders are allowed only 75% of their water right amount – is projected to increase from 14% in the late 20th century to 32% by 2020 and 77% by 2080, assuming no adaptation and under a scenario (A1B) that assumes emissions of heat-trapping gases continue to increase through mid century but decline thereafter (Vano et al. 2010b).

Projected increases in average temperature and hot weather episodes and decreases in summer soil moisture would reduce yields of wheat and other cereals in irrigated and rain-fed production zones. Potential yield losses are expected to reach 25% for some crops by the end of this century, depending upon location, relative to 1975-2005; yields of fully irrigated potatoes are projected to decline by 2% to 3% under the A1B scenario, because the fertilization effect of CO_2 mostly offsets direct climate-related losses (Stöckle et al. 2010). Tuber quality could also be reduced (Alva et al. 2002).

Fully irrigated apple production is projected to increase in Washington state by 6%, 9%, and 16% in the 2020s, 2040s, and 2080s (Stöckle et al. 2010), again with some offsetting between effects of CO_2 and climate. However, because tree fruit requires chilling to ensure uniform flowering and fruit set, and wine grape varieties have specific chilling requirements for maturation (Jones 2005), warming could adversely affect currently grown varieties of these commodities. The economic consequences for Northwest agriculture will be influenced by input and output prices driven by global economic conditions as well as by regional and local changes in productivity.

Adaptive capacity and implications for vulnerability

Of the four areas of concern discussed here, agriculture is perhaps best positioned to adapt to climate trends without explicit planning and policy, because it already responds to annual climate variations and exploits a wide range of existing climates across the landscape (Reilly and Schimmelpfennig 1999). Nonetheless, rapid climate change could present difficulties. Adaptation could occur slowly if substantial investments or significant changes in farm operations and equipment are required. Shifts to new varieties of wine grapes and tree fruit, if indicated, and even if ultimately more profitable, are necessarily slow and expensive. Breeding for drought- and heat-resistance requires long-term effort. Irrigation water shortages that necessitate shifts away from more profitable commodities could exact economic penalties (Washington State Department of Ecology 2011). Risk aversion among farmers, although prudent under typical circumstances, could hamper responsiveness to climatic changes.

Traceable Accounts

Chapter 21: Northwest

Key Message Process: A central component of the assessment process was the NW Regional Climate Risk Framing workshop that was held December 2, 2011 in Portland with approximately 50 attendees. Participants included representatives from all sectors, affiliations, and states and communities within the region to ensure that the outcomes were representative of the region. The workshop consisted of four main components: 1) introduction to risk-based framing of climate impacts; 2) a panel of experts presenting on the likelihood of eight climate risks; 3) an online, real-time survey collecting, from each participant, responses to questions about the consequences of those risks; and 4) breakout group discussions. The survey outcomes and workshop discussions began the process leading to a 79-page Technical Input Report (TIR) that was assembled by 8 authors (Dalton et al. 2012).

The NCA NW chapter author team engaged in multiple technical discussions via regular teleconferences and two all-day meetings. These included careful review of the foundational TIR (Dalton et al. 2012) and of approximately 80 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. They also drew heavily from two state climate assessment reports (CIG 2009; Oregon Climate Change Research Institute 2010). These discussions were followed by expert deliberation of draft key messages by the authors wherein each key message was defended before the entire author team before this key message was selected for inclusion in the Report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities."

Key message #1/4	**Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.**
Description of evidence base	This message was selected because of the centrality of the water cycle to many important human and natural systems of the NW (hydropower production and the users of this relatively inexpensive electricity; agriculture and the communities and economies dependent thereon; coldwater fish, including several species of threatened and endangered salmon, the tribal and fishing communities and ecosystems that depend on them, and the adjustments in human activities and efforts necessary to restore and protect them), these impacts and any societal adjustments to them will have far-reaching ecological and socioeconomic consequences. Evidence that winter snow accumulation will decline under projected climate change is based on 20th century observations and theoretical studies of the sensitivity of NW snowpack to changes in precipitation and temperature. There is good agreement on the physical role of climate in snowpack development, and projections of the sign of future trends are consistent (many studies). However, climate variability creates disagreement over the magnitude of current and near-term future trends. Evidence that projected climate change would shift the timing and amount of streamflow deriving from snowmelt is based on 20th century observations of climate and streamflow and hydrologic model simulation of streamflow responses to climate variability and change. There is good agreement on the sign of trends (many studies), though the magnitude of current and near-term future trends is less certain because of climate variability. Evidence that declining snowpack and changes in the timing of snowmelt-driven streamflow will reduce water supply for many competing and time-sensitive demands is based on: (1) hydrologic simulations, driven by future climate projections, that consistently show reductions in spring and summer flows in transient and some snow-dominant watersheds;

	(2) documented competition among existing water uses (irrigation, power, municipal, in stream flows) and inability for all water systems to meet all summer water needs all of the time, especially during drier years; (3) empirical and theoretical studies that indicate increased water demand for many uses under climate change; (4) policy and institutional analyses of the complex legal and institutional arrangements governing NW water management and the challenges associated with adjusting water management in response to changing conditions. Evidence for far-reaching ecological and socioeconomic consequences of the above is based on: (1) model simulations showing negative impacts of projected climate and altered streamflow on many water resource uses at scales ranging from individual basins (for example, Skagit, Yakima) to the region (for example, Columbia River basin); (2) model simulations of future agricultural water allocation in the Yakima, showing increased likelihood of water curtailments for junior water rights holders; (3) model and empirical studies documenting sensitivity of coldwater fish to water temperatures, sensitivity of water temperature to air temperature, and projected warming of summer stream temperatures; (4) regional and extra-regional dependence on NW-produced hydropower; (5) legal requirements to manage water resources for threatened & endangered fish as well as for human uses. Evidence that water users in managed transient basins (mix of snow and rain) are likely to be the most vulnerable to climate change and less vulnerable in rain dominated basins is based on: (1) observed, theoretical, and simulated sensitivity of watershed hydrologic response to warming by basin type (2) historical observations and modeled simulations of trade-offs required among water management objectives under specific climatic conditions (3) analyses from water management agencies of potential system impacts and adaptive responses to projected future climate (4) institutional and policy analyses documenting sources and types of management rigidity (for example, difficulty adjusting management practices to account for changing conditions)
New information and remaining uncertainties	A key uncertainty is the degree to which current and future interannual and interdecadal variations in climate will enhance or obscure long-term anthropogenic climate trends. Uncertainty over local groundwater or glacial inputs and other local effects may cause overestimates of increased stream temperature based solely on air temperature. However, including projected decreases in summer streamflow would increase estimates of summer stream temperature increases above those based solely on air temperature. Uncertainty in how much increasing temperatures will affect crop evapotranspiration affects future estimates of irrigation demand. Uncertainty in future population growth and changing per capita water use affects estimates of future municipal demand and therefore assessments of future reliability of water resource systems. A major uncertainty is the degree to which water resources management operations can be

	adjusted to account for climate driven changes in the amount and timing of streamflow, and how competing resource objectives will be accommodated or prioritized. Based on current institutional inertia, significant changes are unlikely to occur for several decades. There is uncertainty in economic assessment of the impacts of hydrologic changes on the NW because much of the needed modeling and analysis is incomplete. Economic impacts assessment would require quantifying both potential behavioral responses to future climate-affected economic variables (prices of inputs, products) and to climate change itself. Some studies have sidestepped the issue of behavioral response to these and projected economic impacts based on future scenarios that do not consider adaptation, which lead to high estimates of "costs" or impacts.
Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence	Confidence is **very high** based on strong strength of evidence and **high** level of agreement among experts. See specifics under "description of evidence" above.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 21: Northwest

Key Message Process: See Key Message #1

Key message #2/4	**In the coastal zone, the effects of erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.**
Description of evidence base	Given the extent of the coastline, the importance of coastal systems to the region's ecology, economy, and identity, and the difficulty of adapting in response, the consequences of sea level rise, ocean acidification, and other climate driven changes in ocean conditions and coastal weather are expected to be significant and largely negative, which is why this message was included. Evidence for observed global (eustatic) sea level rise and regional sea level change derives from satellite altimetry and coastal tide gauges. Evidence for projected global sea level rise is described in Ch.2: Our Changing Climate, in the recent NRC report (2012) that includes a detailed discussion of the U.S. west coast, and Parris et al. (2012). Evidence of erosion associated with coastal storms is based on observations of storm damage in some areas of the Northwest. Evidence for erosion and inundation associated with projected sea level rise is based on observations and mapping of coastal elevations and geospatial analyses of the extent and location of inundation associated with various sea level rise and storm surge scenarios. Evidence for climate change impacts on coastal infrastructure derives from geospatial analyses (mapping infrastructure locations likely to be affected by various sea level rise scenarios, storm surge scenarios and/or river flooding scenario), such as those undertaken by various local governments to assess local risks of flooding for the downtown area (Olympia), of sea level rise and storm surge for marine shoreline inundation and risk to public utility infrastructure (Seattle), and of sea level rise for wastewater treatment plants and associated infrastructure (King County). Vulnerability of coastal transportation infrastructure to climate change has been assessed by combining geospatial risk analyses with expert judgment of asset sensitivity to climate risk and criticality to the transportation system in Washington state and by assessing transportation infrastructure exposure to climate risks associated with sea level rise and river flooding in the region as a whole. Evidence for impacts of climate change on coastal habitat is based on: Model-based studies of projected impacts of sea level rise on tidal habitat showing significant changes in the composition and extent of coastal wetland habitats in WA & OR. Observations of extent and location of coastal armoring and other structures that would potentially impede inland migration. Observed changes in coastal ocean conditions (upwelling, nutrients, sea surface temperatures); biogeographical, physiological and paleoecological studies indicating a historical decline in coastal upwelling; global climate model projections of future increases in sea surface temperatures (SST). Modeled projections for increased risk of harmful algal blooms (HAB) in Puget Sound associated with higher air and water temperatures, reduced streamflow, low winds, and small tidal variability (i.e., these conditions offer a favorable HAB window of opportunity). Observed changes in the geographic ranges, migration timing, and productivity of marine species due to changes in sea surface temperatures associated with cyclical events, such as the interannual El Niño Southern Oscillation (ENSO) and inter-decadal Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO).

	Evidence for historical increases in ocean acidification is from observations of changes in coastal ocean conditions, which also indicate high spatial and temporal variability. Evidence for acidification's effects on various species and the broader marine food web is still emerging but is based on observed changes in abundance and size of marine calcifying organisms and laboratory based and in situ acidification experiments. Evidence for marine species responses to climate change derives from observations of shifts in distribution and abundance of marine plankton, fish, and seabird species associated with historical changes in ocean conditions, including temperature and availability of preferred foods. Evidence for low adaptive capacity is from observations of extent of degraded or fragmented coastal habitat, existence of few options for mitigating changes in marine chemical properties, observed extent of barriers to inland habitat migration, narrow coastal transportation corridors, and limited transportation alternatives for rural coastal towns. Evidence for low adaptive capacity is also based on the current limitations (both legal and political) of local and state governments to restrict and/or influence shoreline modifications on private lands.
New information and remaining uncertainties	There is significant but well characterized uncertainty about the rate and extent of future sea level rise at both the global and regional/sub-regional scales. However, there is virtually no uncertainty in the direction (sign) of global sea level rise. There is also a solid understanding of the primary contributing factors and mechanisms causing sea level rise. Other details concerning uncertainty in global sea level rise are treated elsewhere (e.g., NRC 2012) and in Ch.2: Our Changing Climate. Regional uncertainty in projected NW sea level rise results primarily from uncertainty over local vertical land movement (i.e., affecting relative sea level rise). An accurate determination of vertical land deformation requires a sufficient density of monitoring sites (for example, NOAA tide gauges and permanent GPS deformation sites) to capture short wavelength variability, and in most NW coastal locations such dense networks do not exist. There is also considerable uncertainty about potential impacts of climate change on processes that influence storminess and affect coastal erosion in the Northwest. These uncertainties relate to system complexity and the limited number of studies and lack of consensus on future atmospheric and oceanic conditions that will drive changes in regional wind fields. Continued collection and assessment of meteorological data at ocean buoy locations and via remote sensing should improve our understanding of these processes. Uncertainty in future patterns of sediment delivery to the coastal system limit projections of future inundation, erosion and changes in tidal marsh. For example, substantial increases in riverine sediment delivery, due to climate-related changes in the amount and timing of streamflow, could offset erosion and/or inundation projected from changes in sea level alone. However, there are areas in the NW where it is clear that man-made structures have interrupted sediment supply and there is little uncertainty that shallow water habitat will be lost. Although relatively well-bounded, uncertainty over the rate of projected relative sea level rise limits our ability to assess whether any particular coastal habitat will be able to keep pace with future changes through adaptation (for example, through accretion). The specific implications of the combined factors of sea level rise, coastal climate change, and ocean acidification for coastal ecosystems and specific individual species remain uncertain due to the complexity of ecosystem response. However, there is general agreement throughout the peer-reviewed literature that negative impacts for a number of marine calcifying organisms are very likely, particularly during juvenile life stages. Projections of future coastal ocean conditions (for example, temperature, nutrients, pH, productivity) are limited, in part, by uncertainty over future changes in upwelling – climate

	model scenarios show inconsistent projections for likely future upwelling conditions. Considerable uncertainty also remains in whether and how higher average ocean temperatures will influence geographical ranges, abundances, and diversity of marine species, although evidence of changes in pelagic fish species ranges and production associated with Pacific Ocean temperature variability during cyclical events have been an important indicators for potential species responses to climate change in the future. Consequences from ocean acidification for commercial fisheries and marine food web dynamics are potentially very high – while the trend of increasing acidification is very likely, the rate of change and spatial variability within coastal waters are largely unknown and are the subject of ongoing and numerous nascent research efforts. Additional uncertainty surrounds non-climate contributors to coastal ocean chemistry (for example, riverine inputs, anthropogenic carbon, and nitrogen point and non-point source inputs) and society's ability to mitigate these inputs.
Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence	There is **very high** confidence in the global upward trend of sea level rise and ocean acidification. There is **high** confidence that SLR over the next century will remain under an upper bound of approximately 2 meters. Projections for SLR and OA at specific locations are much less certain (**medium to low**) because of the high spatial variability and multiple factors influencing both phenomena at regional and sub-regional scales. There is **medium** confidence in the projections of species response to sea level rise and increased temperatures, but **low** confidence in species response to ocean acidification. Uncertainty in upwelling changes result in **low** confidence for projections of future change that depend on specific coastal ocean temperatures, nutrient contents, dissolved oxygen content, stratification, etc. There is **high** confidence that significant changes in the type and distribution of coastal marsh habitat are likely, but **low** confidence in our current ability to project the specific location and timing of changes. There is **high** confidence in the projections of increased erosion and inundation.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 21: Northwest

Key Message Process: See Key Message #1

Key message #3/4	**The combined impact of increasing wildfire, insect outbreaks, and diseases is virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Almost complete loss of subalpine forests is expected by the 2080s.**
Description of evidence base	Evidence that the area burned by fire has been high relative to earlier in the century since at least the 1980s is strong. Peer-reviewed papers based on federal fire databases (for example, National Interagency Fire Management Integrated Database (NIFMID)1970/1980-2011) and independent satellite data (Monitoring Trends in Burn Severity (MTBS), 1984-2011) indicate increases in area burned. Evidence that the interannual variation in area burned is at least partially controlled by climate during the period 1980-2010 is also strong. Statistical analysis has shown that increased temperature (related to increased potential evapotranspiration, relative humidity, and longer fire seasons) and decreased precipitation (related to decreased actual evapotranspiration, decreased spring snowpack, and longer fire seasons) are moderate to strong (depending on forest type) correlates of the area and number of fires in the Pacific Northwest. Future projections of area burned with climate change are documented in peer-reviewed literature, and different approaches (statistical modeling and dynamic global vegetation modeling) agree on the order of magnitude changes for Pacific Northwest forests, though the degree of increase depends on the climate change scenario and modeling approach. Evidence that the area of forest mortality from insect outbreaks and diseases (including the mountain pine beetle) is increasing is from aerial disease and detection surveys jointly coordinated by the U.S. Forest Service and state level government. Evidence that mountain pine beetle and spruce bark beetle outbreaks are climatically controlled is from a combination of laboratory experiments and mathematical modeling reported in peer-reviewed literature. Peer-reviewed future projections of climate have been used to develop projections of mountain pine beetle and spruce beetle habitat suitability based these models, and show increases in the area of climatically suitable habitat (particularly at mid- to high elevations) by the mid-21st century, but subsequent (late 21st century) declines in suitable habitat, particularly at low- to mid-elevation. There is considerable spatial variability in the patterns of climatically suitable habitat. Evidence for long term changes in the distribution of vegetation types and tree species comes from statistical species models, dynamic vegetation models, and other approaches and uses the correlation between observed climate and observed vegetation distributions to model future climatic suitability. These models agree broadly in their conclusions, that future climates will be unsuitable for historically present species over significant areas of their ranges and that broader vegetation types will likely change, but the details depend greatly on climate change scenario, location within the region, and forest type. Evidence that subalpine forests are likely to undergo almost complete conversion to other vegetation types is moderately strong (relatively few studies, but good agreement), and comes from both dynamic global vegetation models that include climate and individual statistical species distribution models based on climatic variables.

New information and remaining uncertainties	The key uncertainties are primarily the timing and magnitude of future projected changes in forests, rather than the direction (sign) of changes. The rate of expected change is affected by the rate of climate change – higher emissions scenarios have higher impacts earlier in studies that consider multiple scenarios. Most impacts analyses reported in the literature and synthesized here use A1B or A2. Projections of changes in the proportion of NW pine forests where mountain pine beetles are likeliest to survive and of potential conversion of subalpine forests used A2. Statistical fire models do not include changes in vegetation that occur in the 21st century due to disturbance and other factors such as land-use change and fire suppression changes. As conditions depart from the period used for model training, projections of future fire become more uncertain, and by the latter 21st century (beyond about the 2060s-2080s), statistical models may over-predict area burned. Despite this uncertainty, the projections from statistical models are broadly similar to those from dynamic global vegetation models, which explicitly simulate changes in future vegetation. Only a few insects have had sufficient study to understand their climatic linkages, and future insect outbreak damage from other insects currently unstudied could increase the estimate future areas of forest mortality due to insects. Fire-insect interactions and diseases are poorly studied – the actual effects on future landscapes could be greater if diseases and interactions were considered more explicitly. For subalpine forests, what those forests become instead of subalpine forests is highly uncertain – different climate models used to drive the same dynamic global vegetation model agree about loss of subalpine forest, but disagree about what will replace it.
Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence	The observed effects of climate on fires and insects combined with the agreement of future projections across modeling efforts warrants **very high** confidence that increased disturbance will increase forest mortality due to area burned by fire, and increases in insect outbreaks also have very high confidence until at least the 2040s in the Pacific Northwest. The timing and nature of the rates and the sources of mortality may change, but current estimates may be conservative for insect outbreaks due to the unstudied impacts of other insects. But in any case, the rate of projected forest disturbance suggests that changes will be driven by disturbance more than by gradual changes in forest cover or species composition. After that, uncertainty about the interactions between disturbances and landscape response limits confidence to **high** because total area disturbed could begin to decline as most of the landscape becomes outside the range of historical conditions.

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Chapter 21: Northwest

Key Message Process: See Key Message #1

Key message #4/4	**While agriculture's technical ability to adapt to changing conditions can offset some of the adverse impacts of a changing climate, there remain critical sector-specific concerns with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.**
Description of evidence base	NW agriculture's sensitivity to climate change stems from its dependence on irrigation water, adequate temperatures, precipitation and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming trends based on GCMs and emissions scenarios potentially increase temperature-related stress on annual and perennial crops in the summer months. Evidence for projected impacts of warming on crop yields consists primarily of published studies using crop models indicating increasing vulnerability with projected warming over 1975-2005 baselines. These models also project that thermal-stress related losses in agricultural productivity will be offset or overcompensated by fertilization from accompanying increases in atmospheric CO_2. These models have been developed for key commodities including wheat, apples, and potatoes. Longer term, to end of century, models project crop losses from temperature stress to exceed the benefits of CO_2 fertilization. Evidence for the effects of warming on suitability of parts of the region for specific wine grape and tree fruit varieties are based on well-established and published climatic requirements for these varieties. Evidence for negative impacts of increased variability of precipitation on livestock productivity due to stress on range and pasture consists of a few economic studies in states near the region; relevance to NW needs to be established. Evidence for negative impacts of warming on dairy production in the region is based on a published study examining projected summer heat-stress on milk production. Evidence for reduction in available irrigation water is based on peer reviewed publications and state and federal agency reports utilizing hydrological models and precipitation and snowpack projections. These are outlined in more detail in the traceable account for the hydrology section of the NW region chapter. Increased demands for irrigation water with warming are based on cropping systems models and projected increases in acres cultivated. These projections, coupled with those for water supply, indicate that some areas will experience increased water shortages. Water rights records allow predictions of the users most vulnerable to the effects of these shortages. Projections for surface water flows include decreases in summer flow related to changes in snowpack dynamics and reductions in summer precipitation. Although these precipitation projections are less certain than those concerning temperatures, they indicate that water shortages for irrigation will be more frequent in some parts of the region, based especially on a Washington State Department of Ecology sponsored report that considered the Columbia Basin. Other evidence for these projected changes in water is itemized in the Hydrology report for the NW chapter of this report. Evidence that agriculture has a high potential for autonomous adaptation to climate change, assuming adequate water availability, is inferred primarily from the wide range of production practices currently being used across the varied climates of the region.

New information and remaining uncertainties	Although increasing temperatures can affect the distribution of certain pest, weed, and pathogen species, existing models are limited. Without more comprehensive studies, it is not possible to project changes in overall pressure from these organisms, so overall effects remain uncertain. Some may be adversely affected by warming directly or through enhancement of their natural enemy base, while others become more serious. Uncertainty exists in models in how increasing temperatures will impact crop evapotranspiration affects future estimates of irrigation demand (from hydrology) (extracted from Hydrology uncertainty) Shifting international market forces including commodity prices and input costs, adoption of new crops, which may have different heat tolerance or water requirements and technological advances are difficult or impossible to project, but may have substantial effects on agriculture's capacity to adapt to climate change. Estimates of changes in crop yields as a result of changing climate and CO_2 are based on very few model simulations, so the uncertainty has not been well quantified.
Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence	Confidence is **very high** based on strong strength of evidence and high level of agreement among experts. See specifics under "description of evidence" above.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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22. Alaska and the Arctic

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Key Messages

1. **Summer sea ice is receding rapidly and is projected to disappear by mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.**
2. **Most glaciers in Alaska and British Columbia are shrinking, a trend that is expected to continue. This shrinkage contributes 20% to 30% as much to sea level rise as does shrinkage of the Greenland Ice Sheet. Rapid glacier melt in Alaska has implications for hydropower production, ocean circulation patterns, major U.S. fisheries, and global sea level rise.**
3. **Permafrost temperatures in Alaska are rising, a trend that is expected to continue. Thawing permafrost causes multiple vulnerabilities through drier landscapes, more wildfire, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming and jeopardize efforts to offset fossil-fuel emissions through carbon management.**
4. **Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.**
5. The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

Introduction

Alaska is America's only arctic region. Its marine, tundra, boreal (northern) forest, and rainforest ecosystems differ from most of those in other states and are relatively intact. Millions of migratory birds, hundreds of thousands of caribou, some of the world's largest salmon runs, a significant proportion of the nation's marine mammals, and half of the nation's fish catch are found in Alaska (NMFS 2010).

Energy production is the main driver of the state's economy, providing over 80% of state government revenue and thousands of jobs (Leask et al. 2001). Continuing pressure for oil, gas, and mineral development on land and offshore in ice-covered waters increases the demand for infrastructure, placing additional stresses on ecosystems. Climate also affects hydropower generation (Cherry et al. 2010). Mining and fisheries are the second and third largest industries in the state, with tourism rapidly increasing since the 1990s (Leask et al. 2001). Fisheries are vulnerable to changes in fish abundance and distribution that result from both climate change and fishing pressure. Tourism might respond positively to warmer springs and autumns (Yu et al. 2009) but negatively to less favorable conditions for winter activities and increased summer smoke from wildfire (Trainor et al. 2009).

Alaska is home to 40% (229 of 566) of the federally recognized tribes in the U.S. (BIA 2012). The small number of jobs, high cost of living, and rapid social change in rural, predominantly Native communities make them highly vulnerable to climate change through impacts on traditional hunting and fishing and cultural connection to the land and sea. Because most of these communities are not connected to the state's road system or electrical grid, costs are high, and it is challenging to supply food, fuel, materials, health care, and other services. However, Alaskan Native communities have for centuries dealt with scarcity and high environmental variability and thus have deep cultural reservoirs of flexibility and adaptability. Climate impacts on these communities are magnified by additional social and economic stresses.

Observed Climate Change

Over the past 60 years, Alaska has warmed more than twice as rapidly as the rest of the U.S., with state-wide average annual air temperature increasing by 3°F and average winter temperature by 6°F. This warming involves more extremely hot days and fewer extremely cold days (Stewart et al. 2013; U.S. Global Climate Change Science Program 2008). Because of its cold-adapted features and rapid warming, climate-change impacts on Alaska are already pronounced, including earlier spring snowmelt, reduced sea ice, widespread glacier retreat, warmer permafrost, drier landscapes, and more extensive insect outbreaks and wildfire, as described below.

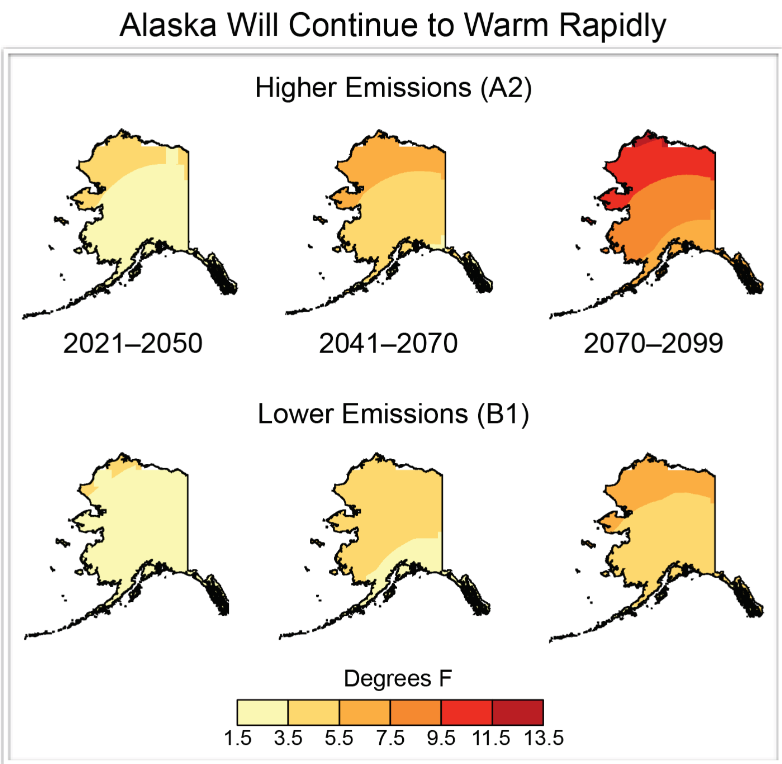

Figure 22.1: Alaska Will Continue to Warm Rapidly

Caption: Northern latitudes are warming faster than more temperate regions, and Alaska has already warmed much faster than the rest of the country. Map shows projected changes in temperature (°F), relative to 1971-1999, projected for Alaska in the early, middle, and late parts of this century, if heat-trapping gas emissions continue to grow (higher emissions, A2), or are substantially reduced (lower emissions, B1). (Figure source: Adapted from Stewart et al. 2013)

Projected Climate Change

Average annual temperatures in Alaska are projected to rise by an additional 2°F to 4°F by the middle of this century. If global emissions continue to increase during this century, temperatures can be expected to rise 10°F to 12°F in the north, 8°F to 10°F in the interior, and 6°F to 8° in the rest of the state. Even with substantial emission reductions, Alaska is projected to warm by 6°F to 8°F in the north and 4°F to 6°F in the rest of the state by the end of the century (Markon et al. 2012; Stewart et al. 2013).

Annual precipitation is projected to increase, especially in northwest Alaska (Stewart et al. 2013). Over the region, the range of model projections for annual precipitation is an increase of 11% to 35%, with an average increase of 25% by late this century if global emissions continue to increase (A2). All models project increases in all four seasons (Stewart et al. 2013). However, increases in evaporation due to higher air temperatures and longer growing seasons are expected to reduce water availability in most of the state (Hinzman et al. 2005). The projected 15 to 25 day increase in length of the snow-free and frost-free seasons (University of Alaska Fairbanks

2012) could improve conditions for agriculture where moisture is adequate, but will reduce water storage and increase the risks of more extensive wildfire and insect outbreaks across much of Alaska (Kasischke et al. 2010; McGuire et al. 2010). Changes in dates of snowmelt and freeze-up would influence seasonal migration of birds and other animals, increase the likelihood and rate of northerly range expansion of native and non-native species, alter the habitats of both ecologically important and endangered species, and affect ocean currents.

Disappearing Sea Ice

Summer sea ice is receding rapidly and is projected to disappear by mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Arctic sea ice extent has declined substantially, especially in late summer when there is now only about half as much sea ice as at the beginning of the satellite record in 1979 (Stroeve et al. 2011). The six Septembers with the lowest ice extent all occurred in the past six years. As sea ice declines, it becomes younger and thinner, and therefore more vulnerable to further melting (Stroeve et al. 2011). Models that best match historical trends project seasonally ice-free northern waters by the 2030s (Stroeve et al. 2007; Wang and Overland 2009, 2012). Within the general downward trend in sea ice there will be periods of a decade or more with both rapid ice loss and temporary recovery (Tietsche et al. 2011), making it challenging to predict short-term changes in ice conditions.

Declining Sea Ice Extent

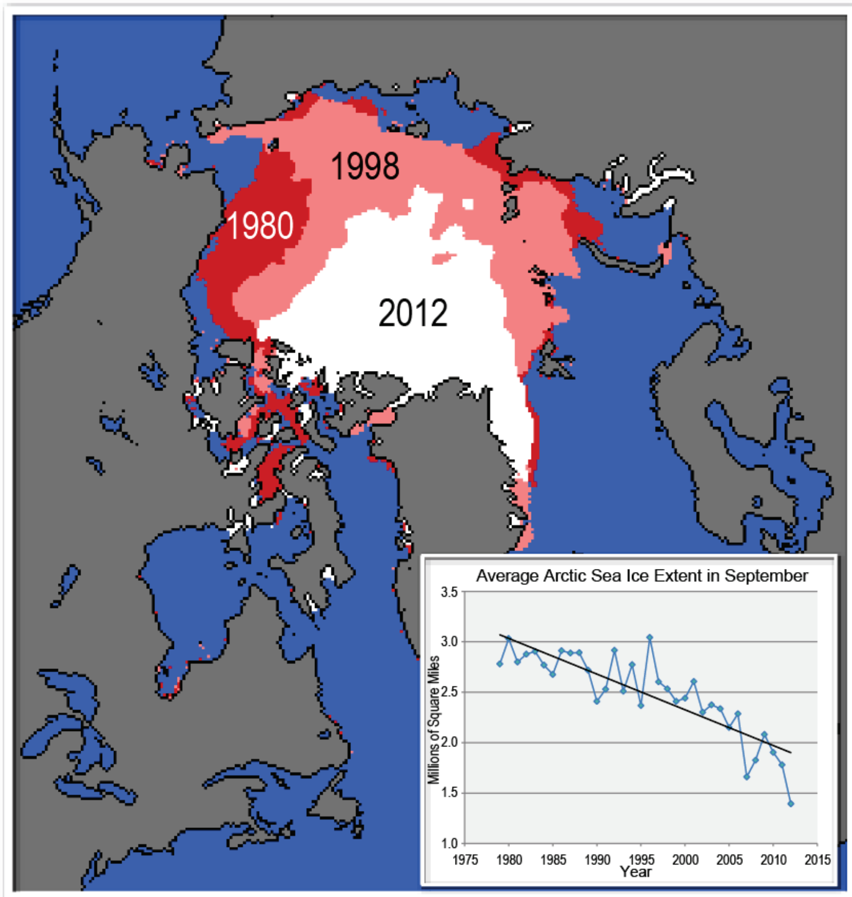

Figure 22.2: Declining Sea Ice Extent

Caption: Average September extent of arctic sea ice in 1980 (second year of record and year of greatest September sea ice extent; outer red boundary), 1998 (about halfway through the time series; outer pink boundary) and 2012 (most recent year of record and year of least September sea ice extent; outer white boundary). September is typically the month when sea ice is least extensive. Inset is the complete time series of average September sea ice extent (Source: NSIDC 2012).

Reductions in sea ice increase the amount of the sun's energy that is absorbed by the ocean. This leads to a self-reinforcing climate cycle, because the warmer ocean melts more ice, leaving more dark open water that gains even more heat. In autumn and winter, there is a strong release of this extra ocean heat back to the atmosphere. This is a key driver of the observed increases in air temperature in the Arctic (Screen and Simmonds 2010; Serreze et al. 2008). This strong warming linked to ice loss can influence atmospheric circulation and patterns of precipitation, both within and beyond the Arctic (for example, Porter et al. 2012). There is growing evidence that this has already occurred (Francis and Vavrus 2012) through more evaporation from the ocean, which increases water vapor in the lower atmosphere (Serreze et al. 2012) and autumn cloud cover west and north of Alaska (Wu and Lee 2012).

Figure 22.3: Sea Ice Loss Brings Big Changes to Arctic Life

Caption: Reductions in sea ice alter food availability for many species from polar bear to walrus, make hunting less safe for Alaska Native hunters, and create more accessibility for Arctic Ocean marine transport. Photographs by Gary Hufford and Carleton Ray; Caleb Pungowiyi; and Patrick Kelley, respectively.

With reduced ice extent, the Arctic Ocean is more accessible for marine traffic, including trans-arctic shipping, oil and gas exploration, and tourism. This facilitates access to the substantial deposits of oil and natural gas under the seafloor in the Beaufort and Chukchi seas, as well as raising the risk to people and ecosystems from oil spills and other drilling and maritime-related accidents. An ice-free Arctic Ocean also increases sovereignty and security concerns as a result of potential new international disputes and increased possibilities for military and commercial marine traffic between the Pacific and Atlantic Oceans (Markon et al. 2012).

Polar bears are one of the most sensitive arctic marine mammals to climate warming because they spend most of their lives on sea ice (Laidre et al. 2008). Declining sea ice in northern Alaska is associated with smaller bears, probably because of less successful hunting of ice-dependent seals (Rode et al. 2010; Rode et al. 2012). Although bears typically give birth to cubs in dens on sea ice, increasing numbers of female bears now come ashore in Alaska in the summer and fall (Schliebe et al. 2008) and den on land (Fischbach et al. 2007). In the western Hudson Bay in eastern Canada, sea ice is now absent for three weeks longer than just a few decades ago, resulting in less body fat, reduced survival of both the youngest and oldest bears (Stirling et al. 1999), and a population now estimated to be in decline (Regehr et al. 2007).

Walrus depend on sea ice as a platform for giving birth, nursing, and resting between dives to the seafloor, where they feed (Fay 1982). In recent years, when summer sea ice in the Chukchi Sea retreated over waters that were too deep for walrus to feed (Douglas 2010), large numbers of walrus abandoned the ice and came ashore. The high concentration of animals results in increased competition for food and can lead to stampedes when animals are startled, resulting in trampling of calves (Fischbach et al. 2009). This movement to land first occurred in 2007 and has happened three times since then, suggesting a threshold change in the ecology of walrus.

With the late-summer ice edge located further north than it used to be, storms produce larger waves and more coastal erosion (Markon et al. 2012). At the same time, coastal bluffs that were "cemented" by permafrost are beginning to thaw in response to warmer air and ocean waters and are therefore more vulnerable to erosion (Overeem et al. 2011). Standard defensive adaptation strategies to protect coastal communities from erosion such as use of rock walls, sandbags, and rip-rap have been largely unsuccessful (State of Alaska 2011). Several coastal communities are seeking to relocate to escape erosion but, because of high costs and policy constraints on use of federal funds for community relocation, only one Alaskan village has begun to relocate (Bronen 2011; U.S. Government Accountability Office 2009) (See also Ch. 12: Tribal Lands and Resources)

Box 1. Living on the Front Lines of Climate Change

"Not that long ago the water was far from our village and could not be easily seen from our homes. Today the weather is changing and is slowly taking away our village. Our boardwalks are warped, some of our buildings tilt, the land is sinking and falling away, and the water is close to our homes. The infrastructure that supports our village is compromised and affecting the health and well-being of our community members, especially our children"

Alaska Department of Commerce and Community and Economic Development, (2012)

Newtok, a Yup'ik Eskimo community on the seacoast of western Alaska is on the front lines of climate change. Between October 2004 and May 2006, three storms accelerated the erosion and repeatedly "flooded the village water supply, caused raw sewage to be spread throughout the community, displaced residents from homes, destroyed subsistence food storage, and shut down essential utilities" (U.S. Army Corps of Engineers 2008a). The village landfill, barge ramp, sewage treatment facility, and fuel storage facilities were destroyed or severely damaged (U.S. Army Corps of Engineers 2008b). The loss of the barge landing, which delivered most supplies and heating fuel, created a fuel crisis. Salt water is intruding into the community water supply. Erosion is projected to reach the school, the largest building in the community, by 2017.

Figure 22.4: Newtok, Alaska

Caption: Residents in Newtok, Alaska are living with the effects of climate change, with thawing permafrost, tilting houses, sinking boardwalks, and aging fuel tanks and other infrastructure that cannot be replaced because of laws that prevent public investment in flood-prone localities. Photograph by Stuart Chapin, 2012.

Recognizing the increasing danger from coastal erosion, Newtok has worked for a generation to relocate to a safer location. However, current federal legislation does not authorize federal or state agencies to assist communities in relocating, nor does it authorize them to repair or upgrade storm-damaged infrastructure in flood-prone locations like Newtok (Bronen 2011). Newtok therefore cannot safely remain in its current location nor can it access public funds to adapt to climate change through relocation.

Newtok's situation is not unique. At least two other Alaskan communities, Shishmaref and Kivalina, also face immediate threat from coastal erosion and are seeking to relocate, but have been unsuccessful in doing so. Many of the world's largest cities are coastal and are increasingly exposed to climate-induced flood risks (Nicholls et al. 2007).

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Shrinking Glaciers

Most glaciers in Alaska and British Columbia are shrinking, a trend that is expected to continue. This shrinkage contributes 20% to 30% as much to sea level rise as does shrinkage of the Greenland Ice Sheet. Rapid glacier melt in Alaska has implications for hydropower production, ocean circulation patterns, major U.S. fisheries, and global sea level rise.

Alaska is home to some of the largest glaciers and fastest loss of glacier ice on Earth (Berthier et al. 2010; Jacob et al. 2012; Larsen et al. 2007), primarily as a result of rising temperatures (for example, Arendt et al. 2009; Arendt et al. 2002; Oerlemans 2005). Loss of glacial volume in Alaska and neighboring British Columbia, Canada currently contributes 20% to 30% as much surplus fresh water to the oceans as does the Greenland Ice Sheet – about 40 to 70 gigatons per year (Jacob et al. 2012; Kaser et al. 2006; Luthcke et al. 2008; Pelto 2011; Pritchard et al. 2010; Van Beusekom et al. 2010), comparable to 10% of the annual discharge of the Mississippi River (Dai et al. 2009). Glaciers continue to respond to climate warming for years to decades after warming ceases, so ice loss is expected to continue, even if air temperatures were to remain at current levels. The global decline in glacial and ice-sheet volume is predicted to be one of the largest contributors to global sea level rise during this century (Meier et al. 2007; Radić and Hock 2011).

Water from glacial landscapes is increasingly recognized as an important source of organic carbon (Bhatia et al. 2010; Hood et al. 2009), phosphorus (Hood and Scott 2008), and iron (Schroth et al. 2011) that contribute to the high productivity of nearshore fisheries (Fellman et al. 2010; Hood and Berner 2009; Hood et al. 2009; Royer and Grosch 2006).

Glaciers supply about half of the total freshwater input to the Gulf of Alaska (Neal et al. 2010). Glacier retreat currently increases river discharge and hydropower potential in southcentral and southeast Alaska but over the longer term might reduce water input to reservoirs and therefore hydropower resources (Cherry et al. 2010).

Thawing Permafrost

Permafrost temperatures in Alaska are rising, a trend that is expected to continue. Thawing permafrost causes multiple vulnerabilities through drier landscapes, more wildfire, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming and jeopardize efforts to offset fossil fuel emissions through carbon management.

Alaska differs from most of the rest of the U.S. in having permafrost – frozen ground that restricts water drainage and therefore strongly influences landscape water balance and the design and maintenance of infrastructure. Alaskan permafrost has warmed about 5°F since the mid-1970s (Osterkamp and Romanovsky 1999; Romanovsky et al. 2010). In Alaska, 73% of land with permafrost is vulnerable to subsidence upon thawing because of its variable-to-high ice content (Jorgenson et al. 2008). Thaw is already occurring in interior and southern Alaska, where permafrost temperatures are near the thaw point (Romanovsky et al. 2010; Romanovsky et al. 2010a). Models project that permafrost in Alaska will continue to thaw (Avis et al. 2011; Euskirchen et al. 2006; Lawrence and Slater 2008), and some models project that near-surface permafrost will be lost entirely from large parts of Alaska by the end of the century (Marchenko et al. 2012).

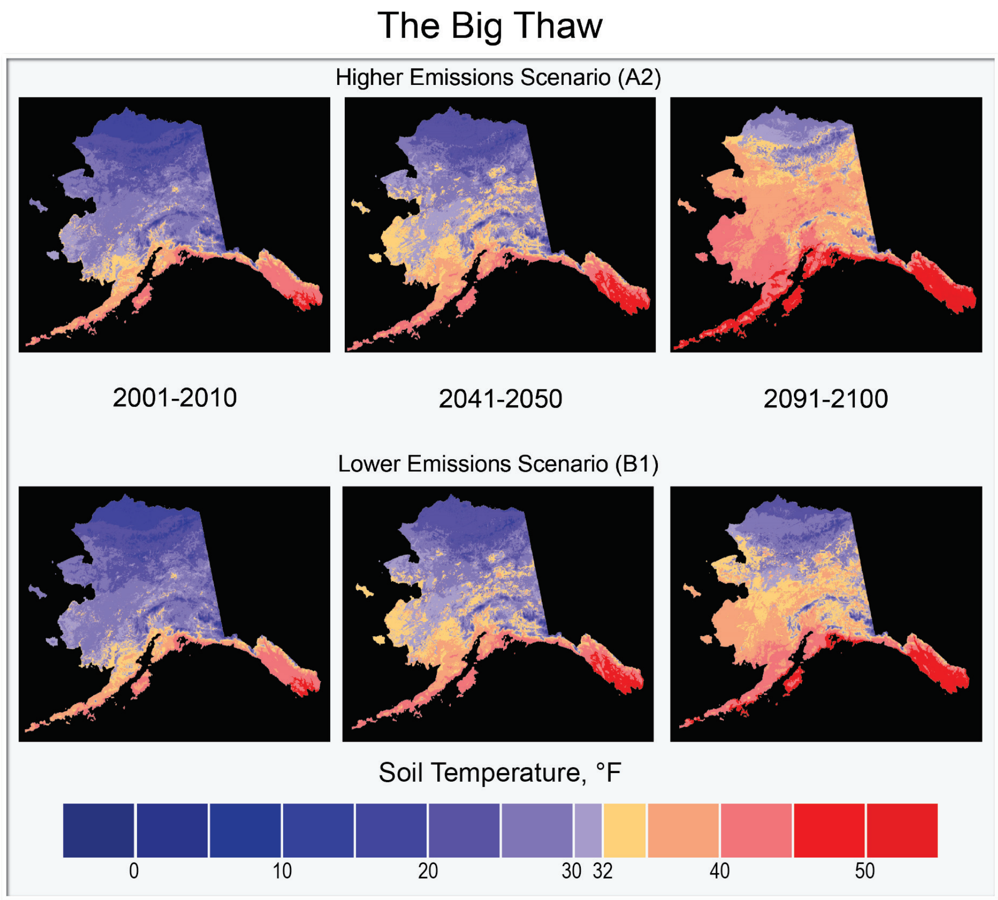

Figure 22.5: The Big Thaw

Caption: Projections for average annual ground temperature at 3.3-foot (one-meter) depth over time if emissions of heat-trapping gases continue to grow (higher emissions scenario, A2), and if they are substantially reduced (lower emissions scenario, B1). Blue shades represent areas below freezing (where permafrost is present at the surface), and yellow and red shades represent areas above freezing (permafrost-free at the surface) (Markon et al. 2012).

Uneven sinking of the ground in response to permafrost thaw is estimated to add between $3.6 and $6.1 billion (10% to 20%) to current costs of maintaining public infrastructure such as buildings, pipelines, roads, and airports over the next 20 years (Larsen et al. 2008). In rural Alaska, permafrost thaw will likely disrupt community water supplies and sewage systems (Alessa et al. 2008; Jones et al. 2009; White et al. 2007), with negative effects on human health (Brubaker et al. 2011). The time during which oil and gas exploration is allowed on tundra has decreased by 50% since the 1970s as a result of permafrost vulnerability (Hinzman et al. 2005).

Mounting Expenses from Permafrost Thawing

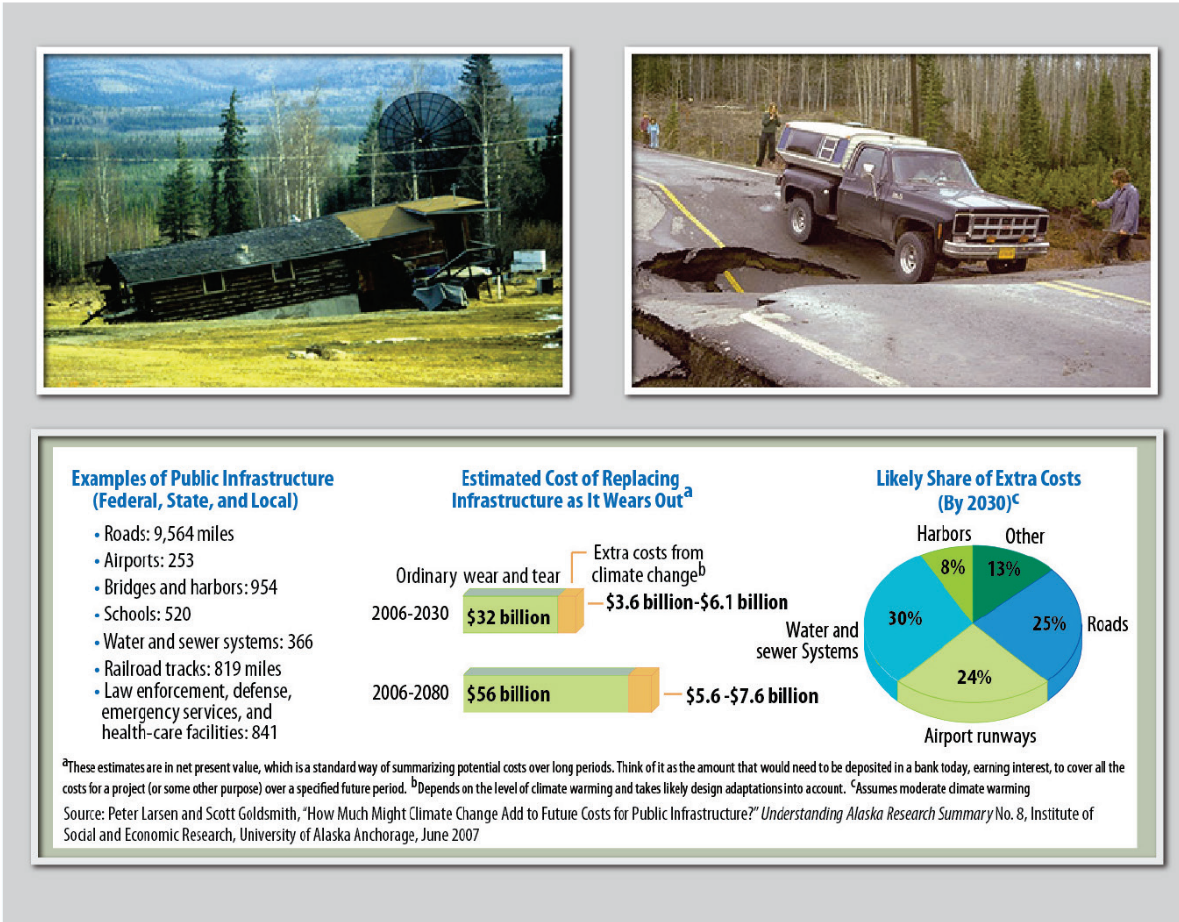

Figure 22.6: Mounting Expenses from Permafrost Thawing

Caption: Effects of permafrost thaw on houses in Interior Alaska (2001, top left), roads in eastern Alaska (1982, top right), and the estimated costs (with and without permafrost thaw) of replacing public infrastructure in Alaska (Larsen et al. 2008). Photographs by Larry Hinzman and Joe Moore.

On average, lakes have decreased in area in the last 50 years in the southern two-thirds of Alaska (Klein et al. 2005; Riordan et al. 2006; Roach 2011; Rover et al. 2012), due to a combination of permafrost thaw, greater evaporation in a warmer climate, and increased carbon accumulation during a longer season for plant growth. In some places, however, lakes are getting larger because of lateral permafrost degradation (Roach et al. 2011). Future permafrost thaw will likely increase lake area in areas of continuous permafrost and decrease lake area in the discontinuous permafrost zone (Avis et al. 2011).

Drying Lakes and Changing Habitat

Figure 22.7: Drying Lakes and Changing Habitat

Caption: Progressive lake drying in northern forest wetlands in the Yukon Flats National Wildlife Refuge, Alaska. Foreground orange area was once a lake. Mid-ground lake once extended to the shrub. Photograph by May-Le Ng.

A continuation of the current drying of Alaskan lakes and wetlands could affect waterfowl management nationally because Alaska accounts for 81% of the National Wildlife Refuge System and provides breeding habitat for millions of migratory birds that winter in more southerly regions of North America and on other continents (Griffith and McGuire 2008). Wetland loss would also reduce waterfowl harvest in Alaska, where it is an important food source for Native Peoples.

Both wetland drying and the increased frequency of warm dry summers and associated thunderstorms have led to more large fires in the last ten years than in any decade since record-keeping began in the 1940s (Kasischke et al. 2010). In Alaskan tundra, which was too cold and wet to support extensive fires for approximately the last 5,000 years (Hu et al. 2010), a single large fire in 2007 released as much carbon to the atmosphere as had been absorbed by the entire circumpolar arctic tundra during the previous quarter-century (Mack et al. 2011). Even if climate warming were curtailed by reducing heat-trapping gas (also known as greenhouse gas) emissions (as in the B1 scenario), the annual area burned in Alaska is projected to double by mid-century and to triple by the end of the century (Balshi et al. 2008), thus fostering a reinforcing cycle of increased heat-trapping gases, higher temperatures, and increased fires. In addition, thick, smog-like smoke produced in years of extensive wildfire represents a human health risk (Alaska Department of Air Quality 2011). More extensive and severe wildfires could shift the forests of Interior Alaska during this century from dominance by spruce to broadleaf trees for the first time in the past 4,000 to 6,000 years (Barrett et al. 2011; Johnstone et al. 2011).

Wildfire has mixed results on habitat: It generally improves habitat for berries, mushrooms, and moose (Maier et al. 2005; Nelson et al. 2008), but reduces winter habitat for caribou because lichens, a key winter food source for caribou, require 50 to 100 years to recover after wildfire (Joly et al. 2010; Rupp et al. 2006). These habitat changes are nutritionally and culturally significant for Alaska Native Peoples (Kofinas et al. 2010; Nelson et al. 2008). In addition, species that were introduced along roadways are now spreading onto river floodplains and recently burned forests (Cortes-Burns et al. 2008; Lapina and Carlson 2004), potentially changing the suitability of these lands for timber production and wildlife. Some invasive species are toxic to moose, on which local people depend for food (Grove 2011).

Changes in terrestrial ecosystems in Alaska and the Arctic may be influencing the global climate system. Permafrost soils throughout the entire Arctic contain almost twice as much carbon as the atmosphere (Schuur and Abbott 2011). Warming and thawing of these soils increases the release of carbon dioxide and methane through increased decomposition and methane production. Thawing permafrost also delivers organic-rich soils to lake bottoms, where decomposition in the absence of oxygen releases additional methane (Walter et al. 2006). Extensive wildfires also release carbon that contributes to climate warming (Balshi et al. 2008; French et al. 2004; Zhuang et al. 2007). The capacity of the Yukon River Basin in Alaska and adjacent Canada to sequester carbon has been substantially weakened since the 1960s by the combination of warming and thawing of permafrost and by increased wildfire (Yuan et al. 2012). Expansion of tall shrubs and trees into tundra makes the surface darker and rougher, increasing absorption of the sun's energy and further contributing to warming (Chapin et al. 2005). The shorter snow-covered seasons in Alaska further increase energy absorption by the land surface, an effect only slightly offset by the reduced energy absorption of highly reflective post-fire snow-covered landscapes (Euskirchen et al. 2009). This spectrum of changes in Alaskan and other arctic terrestrial ecosystems jeopardizes efforts by society to offset fossil fuel emissions through carbon management (McGuire et al. 2009; Schuur and Abbott 2011).

Changing Ocean Temperatures and Chemistry

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes interact to affect the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence (Allison et al. 2011; Cooley and Doney 2009; Doney et al. 2009; Gaines et al. 2003; Pauly 2010; Portner and Knust 2007; Sumaila et al. 2011). These changes have allowed some near-surface fish species such as salmon to expand their range northward along the Alaskan coast (Grebmeier et al. 2010; Grebmeier et al. 2011; Moore and Huntington 2008). In addition, non-native species are invading Alaskan waters more rapidly, primarily through ships releasing ballast waters and bringing southerly species to Alaska (Markon et al. 2012; Ruiz et al. 2000). These species introductions could affect marine ecosystems, including the feeding relationships of commercially important fish.

Overall habitat extent is expected to change as well, though the degree of the range migration will depend upon the life history of particular species. For example, reductions in seasonal sea ice cover and warmer surface temperatures may open up new habitat in polar regions for some important fish species, such as cod, herring, and pollock (Loeng et al. 2005). However, continued presence of cold bottom-water temperatures on the Alaskan continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea off northwest Alaska (Sigler et al. 2011; Stabeno et al. 2012). In addition, warming may cause reductions in the abundances of some species, such as pollock, in the their current ranges in the Bering Sea (Mueter et al. 2011) and reduce the health of juvenile sockeye salmon, potentially resulting in decreased overwinter survival (Farley et al. 2005). If ocean warming continues, it is unlikely that current fishing pressure on pollock can be sustained (Hunt et al. 2011). Higher temperatures are also likely to increase the frequency of early Chinook salmon migrations, making management of the fishery more challenging (Mundy and Evenson 2011).

The North Pacific Ocean has been identified as "a sentinel region for signs of ocean acidification." Acidifying changes in ocean chemistry have potentially widespread impacts on the marine food web, including commercially important species (National Oceanic Atmospheric Administration Ocean Acidification Steering Committee 2010).

Box 2. Ocean Acidification in Alaska

Ocean waters globally have become 30% more acidic due to absorption of large amounts of human-produced carbon dioxide (CO_2) from the atmosphere. This CO_2 interacts with ocean water to form carbonic acid that lowers the ocean's pH (ocean acidification). The polar ocean is particularly prone to acidification because of low temperature (Orr et al. 2005; Steinacher et al. 2009) and low salt content, the latter resulting from the large fresh water input from melting sea ice (Yamamoto-Kawai et al. 2009) and large rivers. Acidity reduces the capacity of key plankton species and shelled animals to form and maintain shells and other hard parts, and therefore alters the food available to important fish species (Lombard et al. 2010; Moy et al. 2009; Orr et al. 2005). The rising acidity will have particularly strong societal effects on the Bering Sea on Alaska's west coast because of its high productivity of commercial and subsistence fisheries (Cooley and Doney 2009; Sambrotto et al. 2008).

Shelled pteropods, which are tiny planktonic snails near the base of the food chain, respond quickly to acidifying conditions and are an especially critical link in high-latitude food webs, as commercially important species such as salmon depend heavily on them for food (Fabry et al. 2009). A 10% decrease in the population of pteropods could mean a 20% decrease in an adult pink salmon's body weight (Mathis 2011). There was a 45% decrease in pteropod consumption by juvenile pink salmon in the northern Gulf of Alaska between 1999 and 2001, although the reason for this decrease is unknown (Armstrong et al. 2005).

At some times of year, acidification has already reached a critical threshold for organisms living on Alaska's continental shelves. Certain algae and animals that form shells such as clams, oysters, and crab, use carbonate minerals (aragonite and calcite) that dissolve below that threshold. These organisms form a crucial component of the marine food web that sustains life in the rich waters off Alaska's coasts. In addition, Alaska oyster farmers are now indirectly affected by ocean acidification impacts further south because they rely for oyster spat (attached oyster larvae) on Puget Sound farmers who are now directly affected by the recent upwelling of acidic waters along the Washington and Oregon coastline (Donkersloot 2012).

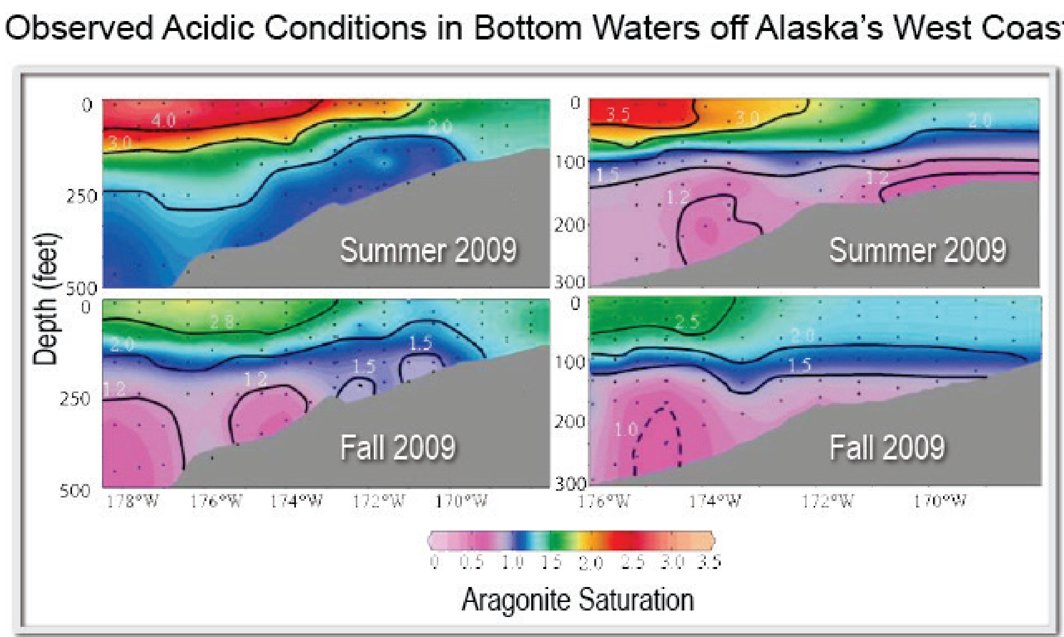

Figure 22.8: Observed Acidic Conditions in Bottom Waters Off Alaska's West Coast

Caption: The acidic conditions under which these minerals (aragonite and calcite) tend to dissolve (known as undersaturation) are shown in the graphs in purple for aragonite and within the dashed lines for calcite. Other colors are favorable for shell formation. Each panel shows the variation in depth of undersaturation along two east-west sampling lines (transect #1 and transect #2) off the west coast of Alaska in summer (upper graphs) and fall (lower graphs). At these sampling times water along the ocean floor was often undersaturated with respect to aragonite but seldom for calcite (Mathis 2011; Mathis et al. 2011). This undersaturation could significantly reduce the capacity of marine animals to produce shells, particularly the commercially important crab species.

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Native Communities

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

With the exception of oil-producing regions in the north, rural Alaska is one of the most extensive areas of poverty in the U.S. in terms of household income, yet residents pay the highest prices for food and fuel (Huskey 1992). Alaska Native Peoples, who are the most numerous residents of this region, depend economically, nutritionally, and culturally on hunting and fishing for their livelihoods (Huntington et al. 2005; Kruse 1991). Hunters speak of thinning sea and river ice that makes harvest of wild foods more dangerous (Berner and Furgal 2005; Loring and Gerlach 2010; McNeeley and Shulski 2011; Moerlein and Carothers 2012), changes to permafrost that alter spring run-off patterns, a northward shift in seal and fish species, and rising sea levels with more extreme tidal fluctuations (Davis 2012; Downing and Cuerrier 2011; Krupnik and Jolly 2002; McNeeley 2012; University of Alaska Fairbanks 2012) (see Ch. 12: Tribal Lands and Resources). Coastal erosion is destroying infrastructure. Impacts of climate change on river ice dynamics and spring flooding are threats to river communities but are complex, and trends have not yet been well documented (Lindsey 2011).

Alaska Coastal Communities Damaged

Figure 22.9: Alaska Coastal Communities Damaged

Caption: One effect of the reduction in Alaska sea ice is that storm surges that used to be buffered by the ice are now causing more shoreline damage. Photos from 2005 show infrastructure damage from coastal erosion in Shishmaref, Alaska. Photographs by Tony Weyiouanna and Gary Braasch.

Major food sources are under stress due to lack of sea ice for marine mammals (Galloway McLean et al. 2009). Thawing of permafrost beneath lakes and ponds that provide drinking water cause food and water security challenges for villages. Sanitation and health problems also result from deteriorating water and sewage systems, and ice cellars traditionally used for storing food are thawing (Alessa et al. 2008; Brubaker et al. 2011) (See also Ch. 12: Tribal Lands and Resources). Warming also brings new diseases to arctic plants and animals, including subsistence food species, posing new health challenges, especially to rural communities

(McLaughlin et al. 2005; Virginia and Yalowitz 2011). Positive health effects of warming include a longer growing season for gardening and agriculture (Markon et al. 2012; Weller 2005).

Development activities in the Arctic (for example, oil and gas, minerals, tourism, and shipping) are of concern to indigenous communities, from both perceived threats and anticipated benefits (Kruse 1991). Greater levels of industrial activity might alter the distribution of species, disrupt subsistence activities, increase the risk of oil spills, and create various social impacts. At the same time, development provides economic opportunities, if it can be harnessed appropriately (Baffrey and Huntington 2010).

Alaska Native Elders say, "We must prepare to adapt." However, the implications of this simple instruction are multi-faceted. Adapting means more than adjusting hunting technologies and foods eaten. It requires learning how to garner information from a rapidly changing environment. Traditional knowledge that enabled people to safely use their environment now provides a guidepost to adapt to climate change as new local observations are linked with western science (Krupnik and Ray 2007; Laidler 2006; Riewe and Oakes 2006). The capacity of Native Peoples to survive for centuries in the harshest of conditions reflects their resilience (Kofinas et al. 2010). Communities must rely not only on improved knowledge of changes that are occurring, but also on strength from within in order to face an uncertain future.

Traceable Accounts

Chapter 22: Alaska and the Arctic

Key Message Process: A central component of the assessment process was the AK Regional Climate assessment workshop that was held September 12-15, 2012 in Anchorage with approximately 20 attendees; it began the process leading to a foundational Technical Input Report (TIR) (Markon et al. 2012). The report consists of 148 pages of text, 45 figures, 8 tables, and 27 pages of references. Public and private citizens or institutions were consulted and engaged in its preparation by the various agencies and NGO's represented by the 11-member TIR writing team. The key findings of the report were presented at the Alaska Forum on the Environment and in a regularly scheduled, monthly webinar by the Alaska Center for Climate Assessment & Policy, with feedback then incorporated into the report.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful review of the foundational TIR (Markon et al. 2012) and of approximately 85 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions were followed by expert deliberation of draft key messages by the writing team in a face-to-face meeting before each key message was selected for inclusion in the Report; these discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities".

Key message #1/5	**Summer sea ice is receding rapidly and is projected to disappear by mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.**
Description of evidence base	The key message and supporting chapter text summarize extensive evidence documented in the AK Technical Input (Markon et al. 2012). Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Although various models differ in the projected rate of sea ice loss, more recent CMIP5 models (Wang and Overland 2012) that most accurately reconstruct historical sea ice loss project that late-summer sea ice will disappear by the 2030s. Evidence (reported by Markon et al. (2012) is strong that sea ice loss is having the impacts highlighted in the key message. Because the sea ice cover plays such a strong role in human activities and Arctic ecosystems, loss of the ice cover is nearly certain to have substantial impacts.
New information and remaining uncertainties	Important new evidence confirmed many of the findings from a prior Alaska assessment; see (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/alaska). Evidence from improved models such as Wang and Overland (2012) and updated observational data from satellite, especially new results from the GRACE satellite, clearly show rapid decline in not only extent but also mass and thickness of multi-year ice that was not available in prior assessments. Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining and that, if heat-trapping gas concentrations continue to rise, an essentially ice-free Arctic ocean will be realized sometime during the 21st century – however there remains uncertainty in the rate of sea ice loss through the 21st century, with the models that most accurately project historical sea ice trends currently suggesting 2021 to 2043 (median 2035).

	Uncertainty across all models stems from a combination of large differences in projections between different climate models, natural climate variability, and future rates of fossil fuel emissions. **Ecosystems:** There is substantial new information that ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes are affecting the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence (Allison et al. 2011; Cooley and Doney 2009; Doney et al. 2009; Pauly 2010; Portner and Knust 2007; Sumaila et al. 2011). However, the relative importance of these potential causes of change is highly uncertain. Regarding offshore development, a key uncertainty is the price of fossil fuels. Viable avenues to improving the information base are determining the primary causes of scatter between different climate models and determining which climate models exhibit the best ability to reproduce the observed rate of sea ice loss. **Coastal erosion:** There is new information that lack of sea ice causes storms to produce larger waves and more coastal erosion (Markon et al. 2012). Also, coastal bluffs that were “cemented” by permafrost are beginning to thaw in response to warmer air and ocean waters and are therefore more vulnerable to erosion (Overeem et al. 2011). Standard defensive adaptation strategies to protect coastal communities from erosion such as use of rock walls, sandbags, and rip-rap have been largely unsuccessful (State of Alaska 2011). There remains considerable uncertainty, however, about the spatial patterns of future coastal erosion.
Assessment of confidence based on evidence	**Very high** confidence for summer sea ice decline. High confidence for summer sea ice disappearing by mid-century. **Very high** confidence for altered marine ecosystems, greater ship access, and increased vulnerability of communities to coastal erosion. **High** confidence regarding offshore development.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 22: Alaska and the Arctic

Key Message Process: See key message #1.

Key message #2/5	**Most glaciers in Alaska and British Columbia are shrinking, a trend that is expected to continue. This shrinkage contributes 20% to 30% as much to sea level rise as does the shrinkage of the Greenland Ice Sheet. Rapid glacier melt in Alaska has implications for hydropower production, ocean circulation patterns, major U.S. fisheries, and global sea level rise.**
Description of evidence base	The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input (Markon et al. 2012). Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence that glaciers in Alaska and British Columbia are shrinking is strong and is based on field studies (Pelto 2011; Van Beusekom et al. 2010), energy balance models (Radić and Hock 2011), LIDAR remote sensing (Arendt et al. 2009; Arendt et al. 2002), and satellite data, especially new lines of evidence from the Gravity and Climate Recovery Experiment [GRACE] satellite (Arendt et al. 2009; Berthier et al. 2010; Luthcke et al. 2008; Pritchard et al. 2010). Evidence is also strong that Alaska ice mass loss contributes to global sea level rise (Meier et al. 2007), with latest results permitting quantitative evaluation of losses globally (Jacob et al. 2012). Numerous peer-reviewed publications (including many that are not cited but included in Markon et al. (2012) describe implications of recent increases, but likely longer-term declines, in water input from glacial rivers to reservoirs and therefore hydropower resources (Cherry et al. 2010; Neal et al. 2010). Since glacial rivers account for 47% of the fresh water input to the Gulf of Alaska (Neal et al. 2010) and are an important source of organic carbon (Bhatia et al. 2010; Hood et al. 2009), phosphorus, (Hood and Scott 2008), and iron (Schroth et al. 2011) that contribute to the high productivity of nearshore fisheries (Fellman et al. 2010; Hood and Berner 2009; Hood et al. 2009; Royer and Grosch 2006), it is quite likely that these changes in discharge of glacial rivers will affect ocean circulation patterns and major U.S. fisheries.
New information and remaining uncertainties	Improved models and observational data (cited above) confirmed many of the findings from prior Alaska assessment; see (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/alaska). As noted above, major advances from GRACE and other datasets now permit analyses of glacier mass loss that were not possible previously. Key uncertainties remain related to large year-to-year variation, the spatial distribution of snow accumulation and melt, and the quantification of glacier calving into the ocean and lakes. Although most large glaciated areas of the state are regularly measured observationally, extrapolation to unmeasured areas carries uncertainties due to large spatial variability. Although there is broad agreement that near-shore circulation in the Gulf of Alaska (GOA) is influenced by the magnitude of freshwater inputs, little is known about the mechanisms of how near-term increases and subsequent longer-term decreases in glacier runoff (as the glaciers disappear) will affect the structure of the Alaska Coastal Current and smaller-scale ocean circulation, both of which have feedback

	to fisheries impacts. The magnitude and timing of effects on hydropower production depend on changes in glacial mass, as described above.
Assessment of confidence based on evidence	**High** confidence that glacier mass loss is high and among the highest on the planet based on physical measurements and satellite observations. **High** confidence that due to glacier mass loss there will be related impacts on hydropower production, ocean circulation and fisheries.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/5	**Permafrost temperatures in Alaska are rising, a trend that is expected to continue. Thawing permafrost causes multiple vulnerabilities through drier landscapes, more wildfire, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming and jeopardize efforts to offset fossil fuel emissions through carbon management.**
Description of evidence base	The key message and supporting chapter text summarize extensive evidence documented in the AK Technical Input (Markon et al. 2012). Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Earlier evidence that permafrost is warming (Osterkamp and Romanovsky 1999) has been confirmed and enhanced by more recent studies (Romanovsky et al. 2010; Romanovsky et al. 2010a), and the most recent modeling efforts (e.g., Avis et al. 2011; Marchenko et al. 2012) extend earlier results (Euskirchen et al. 2006; Lawrence and Slater 2008) and project that permafrost will be lost from the upper few meters from large parts of Alaska by the end of the century. Evidence that permafrost thaw leads to drier landscapes (Roach 2011; Rover et al. 2012) is beginning to accumulate, especially as improved remote sensing tools are applied to assess more remote regions (Avis et al. 2011). Satellite data has expanded the capacity to monitor wildfire across the region, providing additional evidence of wildfire extent. This new evidence has led to increased study that is beginning to reveal impacts on ecosystems and wildlife habitat, but much more work is needed to understand the extent of natural resilience. Impacts of permafrost thaw on the maintenance of infrastructure (Alessa et al. 2008; Hinzman et al. 2005; Jones et al. 2009; Larsen et al. 2008; White et al. 2007) is moderate but rapidly accumulating. Evidence that permafrost thaw will jeopardize efforts to offset fossil fuel emissions is suggestive (McGuire et al. 2009; Schuur and Abbott 2011).
New information and remaining uncertainties	Improved models and observational data confirmed many of the findings from prior Alaska assessment; see (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/alaska). This evidence included results from improved models and updated observational data, and the assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm it relevance and significance for local decision-makers. Key uncertainties involve: 1) the degree to which increases in evapotranspiration vs. permafrost thaw are leading to drier landscapes; 2) the degree to which these drier landscapes associated with permafrost thaw vs. more severe fire weather associated with climate change is leading to more wildfire; 3) the degree to which the costs of the maintenance of infrastructure are associated with permafrost thaw caused by climate change vs. human disturbance of permafrost; and 4) the degree to which climate change is causing Alaska to be a sink versus a source of greenhouse gases to the atmosphere.

Assessment of confidence based on evidence	**Very high** confidence that permafrost is warming. **High** confidence that landscapes in interior Alaska are getting drier, although the relative importance of different mechanisms is not completely clear. **Medium** confidence that thawing permafrost results in more wildfires. There is **high** confidence that wildfires have been increasing in recent decades, even if it is not clear whether permafrost thaw or hotter and drier weather is more important. **High** confidence that climate change will lead to increased maintenance in future decades. Low confidence that climate change has led to increased maintenance costs of infrastructure in recent decades. **Very high** confidence that Alaska is vulnerable to being a source of greenhouse gases to the atmosphere, even though there is not currently strong evidence that Alaska has already become a source of greenhouse gases to the atmosphere.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 22: Alaska and the Arctic

Key Message Process: See key message #1.

Key message #4/5	**Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.**
Description of evidence base	The key message and supporting chapter text summarize extensive evidence documented in the AK Technical Input (Markon et al. 2012). Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications (including many cited in Markon et al. (2012) describe evidence that ocean temperatures are rising and ocean chemistry, especially pH, is changing. New observational data from buoys and ships document increasing acidity and aragonite undersaturation in Alaskan coastal waters. Accumulating strong evidence suggests that these changes in ocean temperature and chemistry, including pH, will likely affect major Alaska marine fisheries, although the relative importance of these changes and the exact nature of response of each fishery are uncertain (Allison et al. 2011; Cooley and Doney 2009; Doney et al. 2009; Gaines et al. 2003; Pauly 2010; Portner and Knust 2007; Sumaila et al. 2011). Alaska's commercial fisheries account for roughly 50 percent of the United States' total wild landings and led all states in terms of both volume and ex-vessel value of commercial fisheries landings in 2009, with a total of 1.84 million metric tons (MT) worth 1.3 billion dollars (NMFS 2010).
New information and remaining uncertainties	Improved models and observational data confirmed many of the findings from prior Alaska assessment; see (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/alaska). This evidence included results from improved models and updated observational data, and the assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm it relevance and significance for local decision-makers. A key uncertainty is what the actual impacts of rising temperatures and changing ocean chemistry, including increase in ocean acidification, will be on a broad range of marine biota and ecosystems. More monitoring is needed to document the extent and location of changes. Additional research is needed to assess how those changes will affect productivity of key fishery resources and their food and prey base.
Assessment of confidence based on evidence	**High** confidence of increased ocean temperatures and changes in chemistry. **Medium** confidence that fisheries will be impacted.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 22: Alaska and the Arctic

Key Message Process: See key message #1.

Key message #5/5	**The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.**
Description of evidence base	The key message and supporting chapter text summarize extensive evidence documented in the AK Technical Input (Markon et al. 2012). Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Evidence exists in recorded local observational accounts as well as in the peer reviewed scientific literature of the cumulative effects of climate-related environmental change on Native communities in Alaska as well as that these effects combine with other socio-economic stressors to strain rural Native communities (Galloway McLean et al. 2009; Huntington et al. 2005; Kruse 1991). Increasing attention to impacts of climate change is revealing new aspects (e.g., Baffrey and Huntington 2010; Brubaker et al. 2011). There is also strong evidence for the cultural adaptive capacity of these communities and peoples over time (Kofinas et al. 2010; Krupnik and Ray 2007; Laidler 2006; Lindsey 2011; Riewe and Oakes 2006).
New information and remaining uncertainties	Improved observational data confirmed many of the findings from prior Alaska assessment; see (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts/alaska). The precise mechanisms by which climate change affects Native communities are poorly understood, especially in the context of rapid social, economic, and cultural change. Adaptive responses are poorly documented. More research is needed on the ways that Alaska Natives respond to biophysical climate change and to the factors that enable or constrain adaptation. Alaska Native communities are already being affected by climate-induced changes in the physical and biological environment, from coastal erosion threatening the existence of some communities, to alterations in hunting, fishing, and gathering practices that undermine the intergenerational transfer of culture, skill, and wisdom. At the same time, these communities have a long record of adaptation and flexibility. Whether such adaptability is sufficient to address the challenges of climate change depends both on the speed of climate-induced changes and on the degree to which Native communities are supported rather than constrained in the adaptive measures they need to make.
Assessment of confidence based on evidence	There is **High** confidence that cumulative effects of climate change in Alaska strongly affect Native communities.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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23. Hawaiʻi and U.S. Affiliated Pacific Islands

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Key Messages

1. **Ocean warming and acidification are producing changes in coastal and ocean ecosystems. Warmer seas are leading to increased coral bleaching events and disease outbreaks in coral reefs, and changed distribution patterns of tuna fisheries. Ocean acidification will lead to reduced calcification rates for corals and coralline algae. Both factors, combined with existing stresses, will strongly affect the fish community of coral reefs.**

2. **Freshwater supplies are already constrained and will be more limited on many Pacific Islands, especially low-lying islands. The quantity and quality of freshwater in aquifers and surface catchments will decline in response to warmer and drier conditions, coupled with increased occurrences of saltwater intrusion associated with sea level rise.**

3. **Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.**

4. **Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.**

5. **Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites. Under these circumstances, it will become increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.**

Introduction

The U.S. Pacific Islands region is vast, comprising more than 2,000 islands spanning millions of square miles of ocean. The largest group of islands in this region, the Hawai‘ian Archipelago, is located nearly 2,400 miles from any continental land mass, which makes it one of the most remote archipelagos on the globe (Loope 1998). The Hawai‘ian islands support fewer than 2 million people, yet provide vital strategic capabilities to U.S. defense – and the islands' biodiversity is important to the world. Hawai‘i and the U.S.-affiliated Pacific Islands are at risk from climate changes that will affect every aspect of life. Rising air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing base flow in streams, rising sea levels, and changing ocean chemistry will affect marine and terrestrial ecosystems, as well as local communities, livelihoods, and cultures. Low islands are particularly at risk.

U.S. Pacific Islands Region

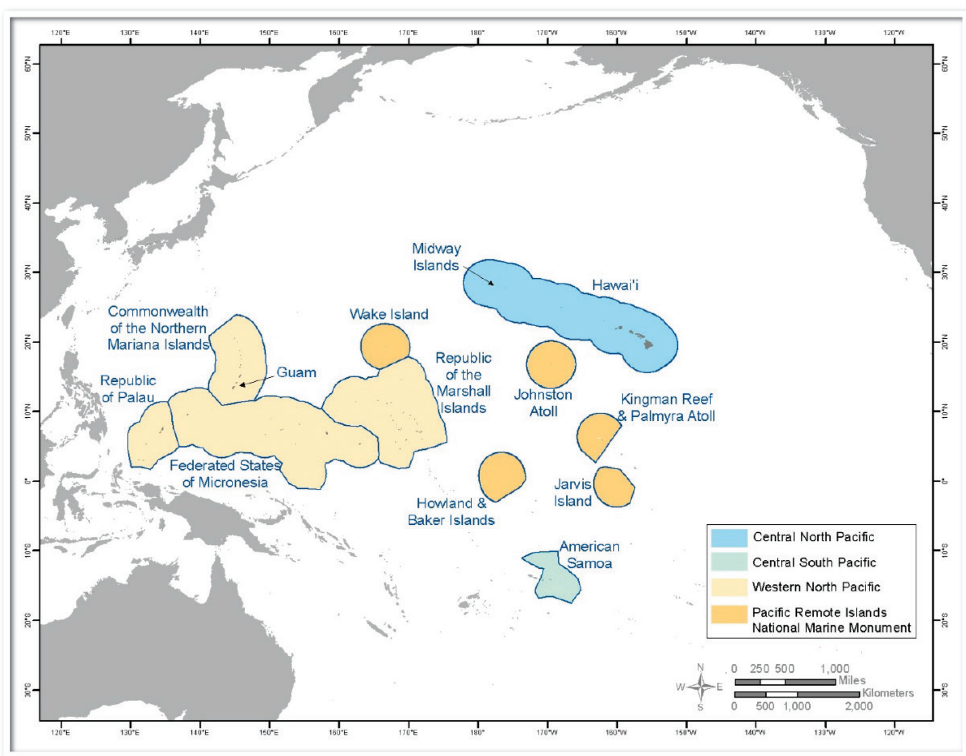

Figure 23.1: U.S. Pacific Islands Region

Caption: The U.S. Pacific Islands region includes our 50th state, Hawai‘i, as well as the Territories of Guam and American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of Marshall Islands (RMI). Citizens of Guam are U.S. citizens and citizens of American Samoa are U.S. nationals. Through the Compacts of Free Association, citizens of CNMI, RP, FSM, and RMI have the right to travel to the U.S. without visas to maintain “habitual residence” and to pursue education and employment. The map shows three sub-regions used in this assessment and the islands that comprise the Pacific Remote Islands National Monument. Shaded areas indicate each island’s Exclusive Economic Zone (EEZ) (Source: Keener et al. 2012). Map courtesy of Miguel Castrence/East-West Center.

U.S. Pacific Islands include volcanic islands, islands of continental crust, atolls (formed by coral reefs), limestone islands, and islands of mixed geologic origin, with tremendous landscape diversity. In the Hawai‘ian high Islands, as many as 10 ecozones – from alpine systems to tropical rainforests – exist within a 25-mile span (Pratt et al. 1998; Ziegler 2002). Isolation and landscape diversity in Hawai‘i brings about some of the highest concentrations of native species, found nowhere else in the world (Ziegler 2002). Several U.S. Pacific Islands are marine biodiversity hotspots, with the greatest diversity found in the Republic of Palau, and the highest percentage of native reef fishes in Hawai‘i (Allen 2008; Fautin et al. 2010). These islands provide insights into evolution and adaptation, concepts important for predicting the impacts of climate change on ecosystems. Their genetic diversity also holds the potential for developing natural products and processes for biomedical and industrial use.

“High” and “Low” Pacific Islands Face Different Threats

The Ko’olau Mountains on the windward side of Oahu, Hawaii. © 2008 kstrebor via Flickr.com, used under a Creative Commons Attribution-ShareAlike license.

Laysan Island, Papahānaumokuākea Marine National Monument, courtesy of Andy Collins/NOAA.

Figure 23.2: “High” and “Low” Pacific Islands Face Different Threats

Caption: The Pacific Islands include “high” volcanic islands that reach nearly 14,000 feet above sea level and “low” atolls and islands that peak at just a few feet above present sea level.

The Pacific Islands region includes demographically, culturally, and economically varied communities of diverse indigenous Pacific Islanders, intermingled with immigrants primarily from Asia, Europe, North America, New Zealand, and Australia. At least 20 languages are spoken in the region. Pacific Islanders recognize the value and relevance of their cultural heritage and systems of traditional knowledge; their laws emphasize the long-term multigenerational connection with their lands and resources (Gegeo 2001; Gegeo and Watson-Gegeo 2001; Teddy et al. 2008). Tourism contributes prominently to the gross domestic product of most island jurisdictions, as does the large U.S. military presence. Geographic remoteness means that the costs of air transport and shipping profoundly influence island economies. Natural resources are limited, with many communities relying on agriculture and ecosystems (such as coral reefs, open oceans, streams, and forests) for sustenance and revenue.

Box 1. High interannual and interdecadal variability of the climate in the Pacific Islands region makes it difficult to discern long-term trends.

The effects of the El Niño-Southern Oscillation (ENSO) on the region are significant. They include large variations in sea surface temperatures, the strength and persistence of the trade winds, the position of the jet streams and storm tracks, and the location and intensity of rainfall (Australian Bureau of Meteorology and CSIRO 2011; IPCC 2007; Kumar and Hoerling 1998; Trenberth 1991; Wyrtki 1975). The ENSO-related extremes of El Niño and La Niña generally persist for 6 to 18 months and change phase roughly every 3 to 7 years (Australian Bureau of Meteorology and CSIRO 2011; D'Aleo and Easterbrook 2010). The Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) are patterns that operate over even longer time horizons and also influence the weather and climate of the region (D'Aleo and Easterbrook 2010; Mantua et al. 1997). This dramatic short-term variability (the noise) can obscure subtle long-term change (the signal) (Deser et al. 2012; Meehl et al. 2009). Despite the challenges of distinguishing natural variability from long-term change, there are several key indicators of observed change that serve as a basis for monitoring and evaluating future change (Keener et al. 2012).

Short-term Variability Continues to Obscure Trends

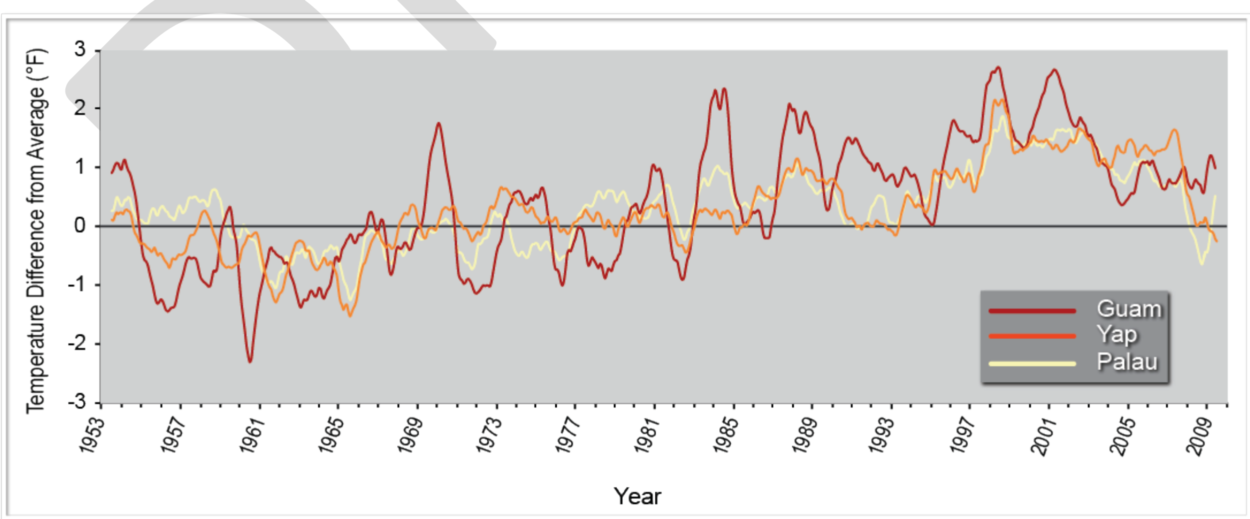

Figure 23.3: Short-term Variability Continues to Obscure Trends

Caption: Average daily maximum temperature for the month relative to the base period average over 1953 to 2010 for single monitoring stations in Yap, Guam, and Palau. The natural patterns of climate in the Pacific such as ENSO, PDO, and IPO continue to make it difficult to discern clear temperature trends on many Pacific islands, although the general trend does follow the global trend of 0.13°F per decade (IPCC 2007) (Adapted from Guard and Lander 2012).

-- end box --

Changes to Marine Ecosystems

Ocean warming and acidification are producing changes in coastal and ocean ecosystems. Warmer seas are leading to increased coral bleaching events and disease outbreaks in coral reefs, and changed distribution patterns of tuna fisheries. Ocean acidification will lead to reduced calcification rates for corals and coralline algae. Both factors, combined with existing stresses, will strongly affect the fish community of coral reefs.

Ocean temperatures in the Pacific region exhibit strong interannual and decadal fluctuations, but since the 1950s they have also exhibited a warming trend, with temperatures from the surface to a depth of 660 feet rising by as much as 3.6°F (Ganachaud et al. 2011).

Future sea surface temperatures are projected to increase 1.1°F (compared to the 1990 levels) by 2030, 1.8°F by 2055, and 2.5°F by 2090 under a scenario that assumes substantial reductions in emissions (B1), or 1.7°F by 2030, 2.3°F by 2055, and 4.7°F by 2090 under a scenario that assumes continued increases in emissions (A2) (Australian Bureau of Meteorology and CSIRO 2011).

Ocean acidification is also taking place in the region. Ocean acidity has increased by about 26% since the preindustrial era and is projected to further increase by 37% to 50% from present levels by 2100 (Feely et al. 2009). The amount of aragonite, the biologically important calcium carbonate mineral critical to reef-building coral and to calcifying algae, will decrease as a result of ocean acidification. Aragonite levels are projected to reach levels that reduce coral growth and survival by 2035 to 2060 around the Pacific, with continuing declines thereafter (Langdon and Atkinson 2005). Crustose coralline algae, an inconspicuous but important component of reefs that help reefs to form and that act as critical surfaces for other organisms to grow on, are also expected to exhibit reduced growth and survival (Diaz‐Pulido et al. 2012; Kline et al. 2012; Kuffner et al. 2008). These changes are projected to have a strong negative impact on the economies and well-being of island communities, with loss of coral biodiversity and reduced resilience (Hoegh-Guldberg et al. 2007).

Bleaching events (as a result of higher ocean temperatures) can weaken or kill corals. At least three mass bleaching episodes have occurred in the Northwestern Hawai‘ian Islands in the last decade (Jokiel and Brown 2004; Kenyon and Brainard 2006). Incidences of coral bleaching have been recorded in Micronesia and American Samoa (Fenner et al. 2008), testing the resilience of these reefs. By 2100, assuming ongoing increases in emissions of heat-trapping gases (A2 scenario), continued loss of coral reefs and the shelter they provide will result in an extensive loss in both numbers and species of reef fishes (Pratchett et al. 2011). Even with a substantial reduction in emissions (B1 scenario), reefs could be expected to lose as much as 40% of their reef-associated fish. Coral reefs in Hawaiʻi provide an estimated $385 million in goods and services annually (Cesar and van Beukering 2004), which could be threatened by these impacts.

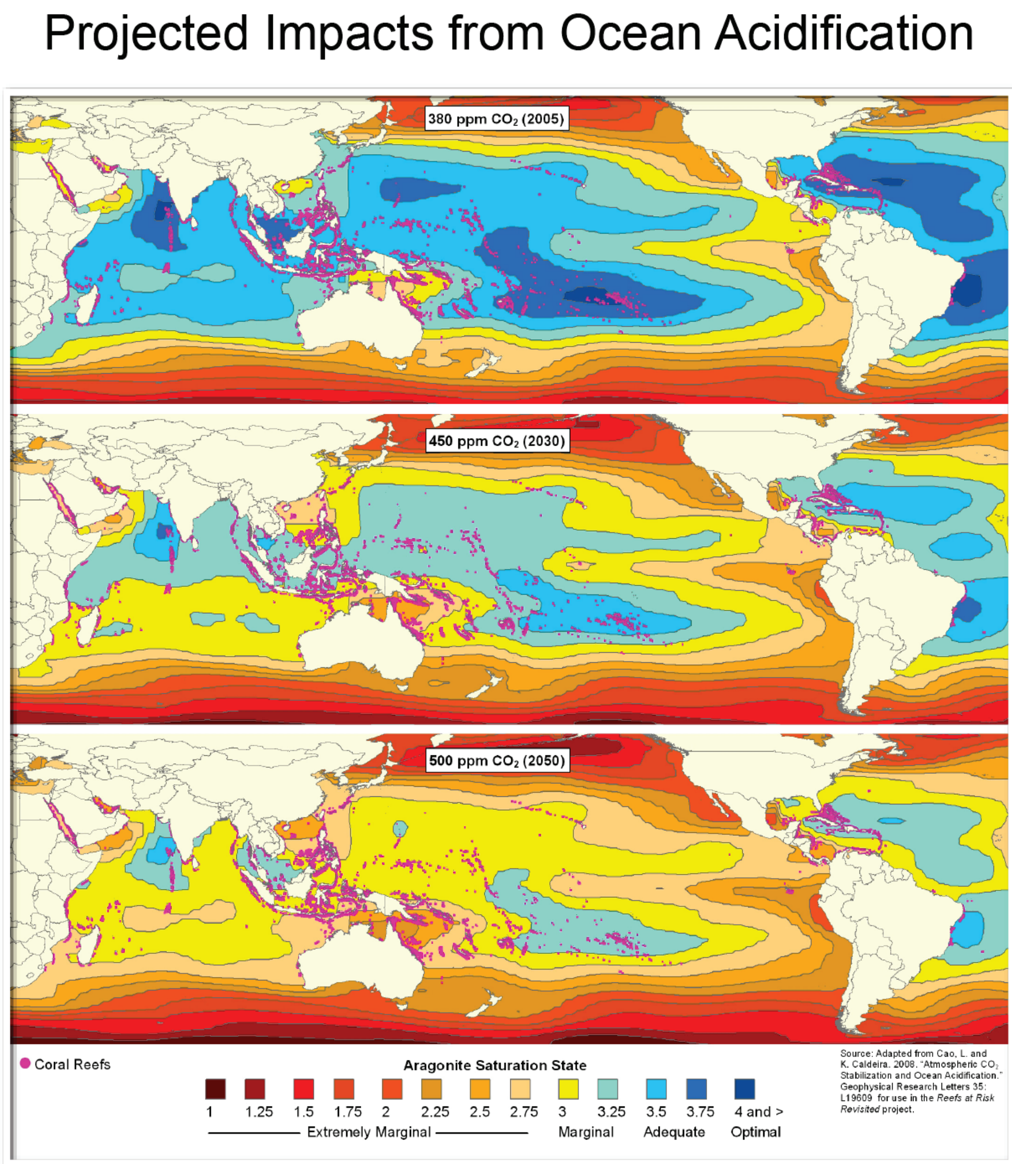

Figure 23.4: Projected Impacts from Ocean Acidification

Caption: Ocean waters have already become more acidic from absorbing carbon dioxide from the atmosphere. In addition to lowering ocean pH, the absorption of CO_2 also has altered the amount of aragonite saturation, which is critical for many marine organisms to reproduce and grow. Maps show projections for aragonite saturation state if CO_2 levels are stabilized at 380 ppm (a level that has already been exceeded), 450 ppm (middle map), and 500 ppm (bottom map), corresponding approximately to the years 2005, 2030, and 2050, assuming some decrease from current emissions trend (scenario A1B). Higher emissions will lead to many more places where aragonite concentrations are "marginal" or "extremely marginal" in much of the Pacific. (In scenario A1B, emissions are similar to scenario A2 through 2050, then reduce towards scenario B1 levels, with emissions in 2100 midway between A2 and B1, while temperatures in 2100 are the same as with A2). Figure used with permission, from Burke and Spalding (2011), (adapted from Cao and Caldeira 2008).

Similarly, impacts to the economically important tuna fishery in the Pacific Island region will be high. Surface chlorophyll data obtained by satellites indicate a decline in an index of productivity in the subtropical South and North Pacific (Polovina et al. 2008) due to warming. This trend is projected to continue under future climate change (Polovina et al. 2011). One fishery model, coupled with a climate model, forecasts that the total fishery catch for skipjack tuna will initially increase by about 19% by 2035 with no change for bigeye tuna. However, by 2100 the catch for both skipjack and bigeye will decline overall by 8% and 27%, respectively, under current emissions trend (A2) for the western and central Pacific, with important spatial differences within the region (Lehodey et al. 2011).

These changes to both corals and fish pose threats to communities, cultures, and ecosystems of the Pacific Islands both directly through their impact on food security and indirectly through their impact on economic sectors including fisheries and tourism.

Decreasing Freshwater

Freshwater supplies are already constrained and will be more limited on many Pacific Islands, especially low islands. The quantity and quality of freshwater in aquifers and surface catchments will decline in response to warmer, drier conditions coupled with increased occurrences of saltwater intrusion associated with sea level rise.

Surface air temperature has increased and is expected to continue to increase over the entire region (Giambelluca et al. 2008). In Hawaiʻi, the rate of increase has been greater at high elevations (Giambelluca et al. 2008). In Hawaiʻi and the Central North Pacific, projected annual surface air temperature increases range from 1.5°F by 2055 (relative to 1971-2000) under a scenario of substantial emissions reduction (B1) to 3.5°F assuming continued increases in emissions (A2) (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific, the projected increases are 1.9°F and 2.6°F by 2055 under the B1 and A2 scenarios, respectively (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific, projected annual surface air temperature increases are 1.9°F and 2.5°F by 2055 under the B1 and A2 scenarios (Australian Bureau of Meteorology and CSIRO 2011).

In Hawaiʻi, average precipitation, average stream discharge, and stream base flow have been trending downward for nearly a century, especially in recent decades, but with high variability due to cyclical climate patterns such as ENSO and the PDO (Bassiouni and Oki 2012; Chu and Chen 2005; Oki 2004). For the Western North Pacific, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region, and slight upward trends in precipitation have been seen for the western-most islands with high ENSO-related variability (Bailey and Jenson 2011; Ganachaud et al. 2011). In American Samoa, no trends in average rainfall are apparent, but there is very limited available data (Ganachaud et al. 2011; Young 2007).

Projections of precipitation are less certain than those for temperature (Keener et al. 2012). For Hawaiʻi, a scenario based on statistical downscaling projects a 5% to 10% reduction for the wet season and a 5% increase in the dry season for the end of this century (Timm and Diaz 2009). Projections for late this century from global models for the region give a range of results. Generally they predict annual rainfall to either change little or to increase by up to 5% for the main Hawaiʻian Islands, change little or decrease up to 10% in the Northwest Hawaiʻian Islands, and increase 5% to 15% in the U.S.-affiliated islands of Micronesia (Christensen et al. 2007).

Climate change impacts on freshwater resources in the Pacific Islands will vary across the region. Different islands will be affected by different factors, including natural variability patterns that affect storms and precipitation (like El Niño and La Niña events), as well as climate trends that are strongly influenced by specific geographic locations. Climate change impacts on freshwater resources in the region will also vary because of differing island size and topography, which affect water storage capability and susceptibility to coastal flooding. On most islands, increased temperatures coupled with decreased rainfall and increased drought will increase the need for, and reduce the amount of, freshwater available for drinking and crop irrigation (Döll 2002; Sivakumar and Hansen 2007). Low-lying islands will be particularly vulnerable due to their small land mass, geographic isolation, limited potable water sources, and agricultural resources (Barnett and Adger 2003). Also, as sea level rises over time, increasing intrusion of saltwater from the ocean during storms will exacerbate the situation. These are only part of a cascade of climate change related impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities (Storlazzi et al. 2011).

Observed Changes in Annual Rainfall in the Western North Pacific

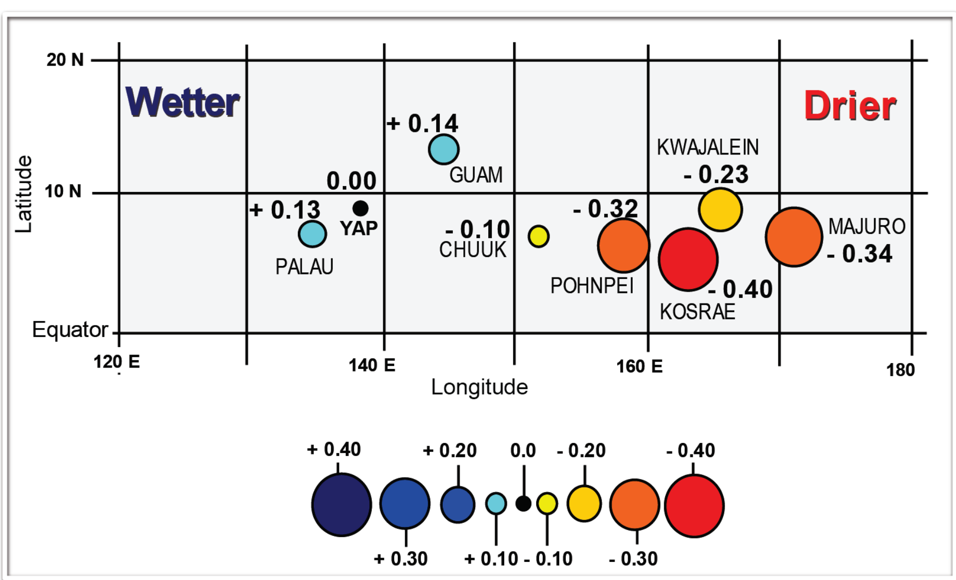

Figure 23.5: Observed Changes in Annual Rainfall in the Western North Pacific

Captions: Islands in the west are getting slightly more rainfall than in the past, while islands in the east are getting drier (measured in change in inches of monthly rainfall per decade over the period 1950-2010). Darker blue shading indicates that conditions are wetter, while darker red shading indicates drier conditions. The size of the dot is proportional to the size of the trend as per the inset scale. (Source: Modified and updated from Lander 2004; Lander and Guard 2003).

Increased Stress on Native Plants and Animals

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Projected climate changes will significantly alter the distribution and abundance of many native marine, terrestrial, and freshwater species in the Pacific islands. The vulnerability of coral reef and ocean ecosystems was discussed earlier. With respect to land-based and freshwater species, high elevation ecosystems in high islands, as well as low-lying coastal ecosystems on all islands, are especially vulnerable. Existing climate zones on high islands are generally projected to shift upslope in response to climate change (Benning et al. 2002). The ability of native species to adapt to shifting habitats will be affected by ecosystem discontinuity and fragmentation, as well as the survival or extinction of pollinators and seed dispersers. Some (perhaps many) invasive plant species will have a competitive edge over native species, as they disproportionately benefit from increased carbon dioxide, disturbances from extreme climate events, and an ability to invade higher elevation habitats as climates warm (Bradley et al. 2010). Hawaiʻian high-elevation alpine ecosystems on Hawai`i and Maui islands are already beginning to show strong signs of increased drought and higher temperatures (Cao et al. 2007). For example, the number of Haleakalā silversword, a rare plant that is an integral component of the alpine ecosystem in Haleakalā National Park in Maui and is found nowhere else on the planet, has declined dramatically over the past two decades (Krushelnycky et al. 2012). Many of Hawaiʻi's native forest birds, marvels of evolution largely limited to high-elevation forests by predation and disease, are increasingly vulnerable as rising temperatures allow mosquitoes carrying diseases like avian malaria to thrive upslope and thereby reduce the extent of safe bird habitat (Benning et al. 2002; LaPointe et al. 2012).

Native Plants at Risk

Figure 23.6: Native Plants at Risk

Caption: Warming at high elevations could alter the distribution of native plants and animals in mountainous ecosystems and increase the threat of invasive species. The threatened, endemic ʻahinahina or Haleakalā silversword (*Argyroxiphium sandwicense subsp. macrocephalum*), shown here in full bloom on Maui, Hawaiʻian Islands, is one example. Photo courtesy of Forest & Kim Starr.

On high islands like Hawaiʻi, decreases in precipitation and base flow are already indicating that there will be impacts on freshwater ecosystems and aquatic species (Oki 2004; Young 2007). Many Pacific Island freshwater fishes and invertebrates have oceanic larval stages in which they seasonally return to high island streams to aid reproduction (Keith 2003; Maciolek 1983). Changes in stream flow and oceanic conditions that affect larval growth and survival will alter the ability of these species to maintain viable stream populations.

Sea Level Rising

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Global average sea level has risen by about 8 inches since 1900 (Church and White 2011), with recent satellite observations indicating an increased rate of rise over the past two decades (1.3 inches per decade) (Nerem et al. 2010)(See also Ch. 2: Our Changing Climate, Key Message 9). Recent regional sea level trends in the western tropical Pacific are higher (Becker et al. 2012; Merrifield 2011; Timmermann et al. 2010) than the global average, due in part to changing wind patterns associated with natural climate variability (Di Lorenzo et al. 2010; Feng et al. 2010; Merrifield and Maltrud 2011; Merrifield et al. 2012; Meyssignac et al. 2012). Over this century, sea level in the Pacific is expected to rise at about the same rate as the projected increase in global average sea level, with regional variations associated with ocean circulation changes and the Earth's response to other large-scale changes, such as melting glaciers and ice sheets as well as changing water storage in lakes and reservoirs (Stammer et al. 2012).

Rising sea levels will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, waste water systems, shallow coral reefs, sea grass beds, intertidal flats and mangrove forests, and other social, economic, and natural resources. Impacts will vary with location depending on how regional sea level variability combines with increases of global average sea level (Marra et al. 2012). On low islands, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming (Easterling et al. 2007) and periodic flooding increases the salinity of groundwater. Coastal and near shore environments will progressively be affected as sea levels rise and high wave events alter low islands' size and shape. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10% to 20% in total regional mangrove area over the next century (Gilman et al. 2008). This would in turn reduce the nursery areas and feeding grounds for fish species, habitat for crustaceans and invertebrates, shoreline protection and wave dampening, and water filtration provided by mangroves (Waycott et al. 2011). Pacific seabirds that breed on low-lying atolls will lose large segments of their breeding populations (Arata et al. 2009) as their habitat is increasingly and more extensively covered by seawater.

Figure 23.7: Saltwater Intrusion Destroys Crops

Caption: Taro crops destroyed by encroaching saltwater at Lukunoch Atoll, Chuuk State, FSM. Giant swamp taro is a staple crop in Micronesia that requires a two- to three-year growing period from initial planting to harvest. After a saltwater inundation from a storm surge or very high tide, it may take two years of normal rainfall to flush brackish water from a taro patch, resulting in a five-year gap before the next harvest if no further saltwater intrusion takes place. Photo courtesy of John Quidachay/USDA Forest Service.

Impacts to the built environment on low-lying portions of high islands, where nearly all airports are located and where each island’s road network is sited (Mimura et al. 2007), will be nearly as profound as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. In Hawai‘i, for example, where tourism comprises 26% of the state’s economy, damage to tourism infrastructure – including the loss of Waikīkī Beach – could lead to an annual loss of $2 billion in visitor expenditures (Waikīkī Improvement Association 2008).

Threats to Lives, Livelihoods, and Cultures

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites. Under these circumstances, it will become increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

All of the climate change impacts described above will have an impact on human communities in Pacific Islands. Because Pacific Islands are almost entirely dependent upon imported food, fuel, and material, the vulnerability of ports and airports to extreme events, sea level rise, and increasing wave heights is of great concern. Climate change is expected to have serious effects on human health by increasing the incidence of dengue fever, for example (Lewis 2012). In addition, sea level rise and flooding are expected to overcome sewer systems and threaten public sanitation. Finally, the traditional lifestyles and cultures of indigenous communities in all Pacific Islands will be seriously affected by climate change. Sea level rise and associated flooding is expected to destroy coastal artifacts and structures (Vitousek et al. 2004) or even the entire land base associated with cultural traditions (Henry and Jeffery 2008). Drought threatens traditional food sources such as taro and breadfruit, and coral death from warming-induced bleaching will threaten subsistence fisheries in island communities (Maclellan 2009). Climate-related environmental deterioration for communities at or near the coast, coupled with other socioeconomic or political motivations, is expected to lead individuals, families, or communities to consider moving to a new location. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Residents of Low-lying Islands at Risk

Figure 23.8: Residents of Low-lying Islands at Risk

Caption: Residents of places like the Namdrik Atoll in the Republic of the Marshall Islands, with a land area of just 1.1 square miles and a maximum elevation of 10 feet, may be among the first to face the possibility of climate-induced human migration as sea level continues to rise. Photo courtesy of Darren Nakata.

Higher Sea Level Rise in Western Pacific

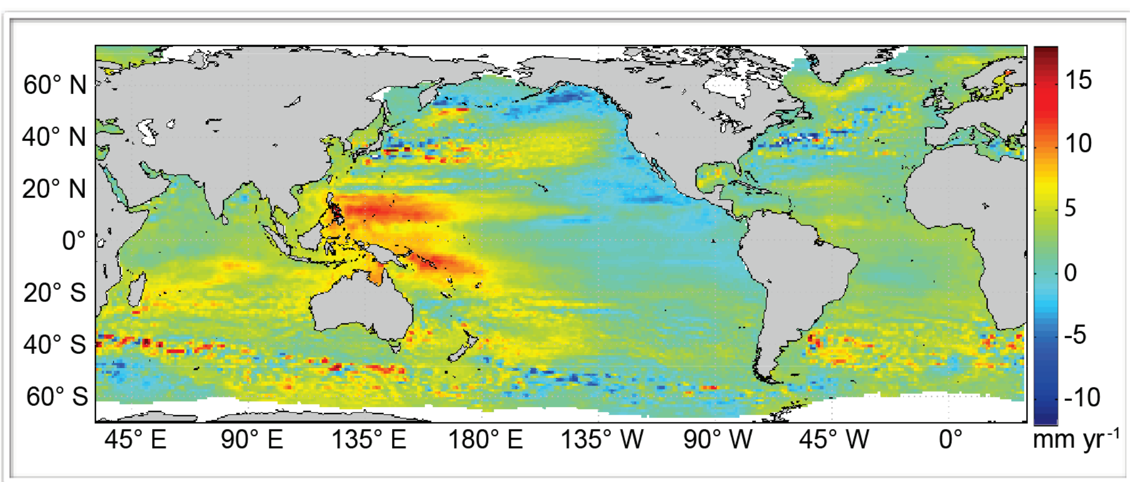

Figure 23.9: Higher Sea Level Rise in Western Pacific

Caption: Map shows large variations across the Pacific Ocean in the trend in sea level for 1993-2010. The largest increase in sea level has been observed in the western Pacific. *Source:* Merrifield (2011), by permission of American Meteorological Society.

Adaptation Activities

Adaptive capacity in the region varies and reflects the histories of governance, the economies, and the geographical features of the island/atoll site. High islands can better support larger populations and infrastructure, attract industry, foster institutional growth, and thus bolster adaptive capacity (Keener et al. 2012); but these sites have larger policy or legal hurdles that complicate coastal planning (Codiga and Wager 2011). Low islands have a different set of challenges. Climate change related migration, for example, is particularly relevant to the low island communities in the RMI and the FSM, and presents significant practical, cultural, and legal challenges (Burkett 2011).

In Hawaiʻi, state agencies have drafted a framework for climate change adaptation by identifying sectors affected by climate change and outlining a process for coordinated statewide adaptation planning (Group 70 International 2009; Townscape Inc. 2009). Both Hawaiʻi and American Sāmoa specifically consider climate change in their U.S. Federal Emergency Management Agency (FEMA) hazard mitigation plans, and the Commonwealth of Northern Mariana Islands lists climate variability as a possible hazard related to extreme climate events (Anderson 2012a). The U.S. Pacific Island Freely Associated States (which includes the FSM, RP, and RMI) have worked with regional organizations to develop plans and access international resources. Each of these jurisdictions has developed a status report on integrating climate-related hazard information in disaster risk reduction planning and has developed plans for adaptation to climate-related disaster risks (Anderson 2012b). Overall, there is very little research on the effectiveness of alternative adaptation strategies for Pacific Islands and their communities. The regional culture of communication and collaboration provides a strong foundation for adaptation planning and will be important for building resilience in the face of the changing climate.

Traceable Accounts

Chapter 23: Hawai‘i and Pacific Islands

Key Message Process: A central component of the assessment process was convening three focus area workshops as part of the Pacific Islands Regional Climate Assessment (PIRCA). The PIRCA is a collaborative effort aimed at assessing the state of climate knowledge, impacts, and adaptive capacity in Hawai‘i and the U.S.-Affiliated Pacific Islands. These workshops included representatives from the U.S. federal agencies, universities, as well as international participants from other national agencies and regional organizations and led to the formulation of a foundational TIR report (Keener et al. 2012). The report consists of nearly 140 pages, with almost 300 references, that were organized into 5 chapters by 11 authors.

The chapter author team engaged in multiple technical discussions via regular teleconferences that permitted a careful review of the foundational TIR (Keener et al. 2012) and of approximately 23 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions included a face-to-face meeting held on July 9, 2012. These discussions were supported by targeted consultation among the lead and contributing authors of each message that included several iterations of review and comment on draft key messages and associated content.

Key message #1/5	**Ocean warming and acidification are producing changes in coastal and ocean ecosystems. Warmer seas are leading to increased coral bleaching events and disease outbreaks in coral reefs, and changed distribution patterns of tuna fisheries. Ocean acidification will lead to reduced calcification rates for corals and coralline algae. Both factors, combined with existing stresses, will strongly affect the fish community of coral reefs.**
Description of evidence base	The key message was chosen based on input from the extensive evidence documented in the Hawai‘i Technical Input (Keener et al. 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Key message 11 in Chapter 2, Our Changing Climate, and its traceable account also provides evidence for ocean acidification. Ocean warming: There is ample evidence that sea-surface temperatures have already risen throughout the region based on clear observational data, with improved data with the advent of satellite and in-situ (ARGO & ship-based) data. Assessment of the literature for the region by other governmental bodies (i.e. ABOM and CSIRO) point to continued increases under both B1 and A2 scenarios. Acidification; Historical and current observations of aragonite saturation state (Ωar) for the Pacific Ocean show a decrease from approximately 4.9 to 4.8 in the Central North Pacific; in the Western North Pacific it has declined from approximately 4.5 to 3.9 in 2000, and to 4.1 in the Central South Pacific (Feely et al. 2009) (Figure 4 in Chapter 23, Hawai‘i and Pacific Islands and available in the Oceans and Marine Resources chapter). Projections from CMIP3 models indicate the annual maximum aragonite saturation state will reach values below 3.5 by 2035 in the waters of the Republic of the Marshall Islands (RMI), by 2030 in the Federated States of Micronesia (FSM), by 2040 in Palau, and by 2060 around the Samoan archipelago. These values are projected to continue declining thereafter (Citations in (Keener et al. 2012), including those of other governmental bodies such as CSIRO). The recently published Reefs at Risk Revisited estimates aragonite saturation state (as an indicator of ocean acidification) for CO2 stabilization levels of 380 ppm, 450 ppm and 500 ppm, which correspond approximately to the years 2005, 2030, and 2050 under the IPCC A1B emissions

	scenario (Figure 4.4 from Keener et al. 2012). Bleaching events: These have been well-documented in extensive literature world-wide due to increasing temperatures, with numerous studies in Hawaiʻi and the Pacific Islands. Disease outbreaks: Reports of coral diseases have been proliferating in the past years, but few have currently been adequately described, with causal organisms identified (e.g. fulfill Koch's Postulates). Reduced growth: There is abundant evidence from laboratory experiments that lower seawater pH reduces calcification rates in marine organisms (e.g., Feely et al. 2009), however, actual measurements on the effects of ocean acidification on coral reef ecosystems *in situ* or in complex mesocosms are just now becoming available and show that there are large regional and diel variability in pH and pCO2. The role of diel and regional variability on coral reef ecosystems requires further investigation. Distribution patterns of coastal and ocean fisheries: The effects of ocean acidification on U.S. fisheries in Hawaiʻi and the U.S. affiliated Pacific Islands is currently limited ((Lehodey et al. 2011) but which illustrates accumulating evidence for ecosystem impacts.
New information and remaining uncertainties	New information: Since the 2009 assessment, considerable effort has been employed to understand the impacts of ocean acidification (OA) on marine ecosystems, with recent ecosystem based efforts such as (Kline et al. 2012; Lehodey et al. 2011) as examples. Studies of OA impacts on organisms has advanced considerably, with careful chemistry using worldwide standard protocols making inroads into understanding a broadening range of organisms. However, predicting the effect of ocean acidification on marine organisms and marine coral reef ecosystems remains the key issue, with the role of community metabolism and calcification in the face of overall reduction in aragonite saturation state must be investigated. Interaction of rising temperature and OA remains a challenge. For example, temperature simultaneously causes coral bleaching, as well as affect coral calcification rates, with both impacts projected to increase in the future.
Assessment of confidence based on evidence	There is **very high** confidence that ocean acidification and decreased aragonite saturation is taking place and is projected to continue.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 23: Hawai‘i and Pacific Islands

Key Message Process: See KM#1.

Key message #2/5	**Freshwater supplies are already constrained and will be more limited on many Pacific Islands, especially low-lying islands. The quantity and quality of freshwater in aquifers and surface catchments will decline in response to warmer and drier conditions, coupled with increased occurrences of saltwater intrusion associated with sea level rise.**
Description of evidence base	As with the US, and globally (Ch. 2: Our Changing Climate, Key Message 3), there is abundance and definitive evidence that air temperature has increased, and is projected to continue to increase over the entire region (Australian Bureau of Meteorology and CSIRO 2011; Giambelluca et al. 2008; Lander 2004; Lander and Guard 2003) In Hawai’i and the Central North Pacific (CNP) projected annual surface air temperature increases are 1.0-2.5°F by 2035 relative to 1971-2000 (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific (WNP) the projected increases are 2.0-2.3°F by 2030, 6.1°F -8.5°F by 2055, and 4.9-9.2°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific (CSP) projected annual surface air temperature increases are 1.1-1.3°F by 2030, 1.8-2.5°F by 2055 and 2.5-4.9°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011) . In Hawai’i mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high ENSO and PDO-related variability (Bassiouni and Oki 2012; Chu and Chen 2005; Oki 2004). For the WNP, a decline of 15% in annual rainfall has been observed in the eastern-most islands in Micronesia region and slight upward trends in precipitation have been seen for the western-most islands with high ENSO-related variability (Australian Bureau of Meteorology and CSIRO 2011; Bailey and Jenson 2011). In American Samoa, no trends in average rainfall are apparent based on the very limited available data (Australian Bureau of Meteorology and CSIRO 2011; Young 2007). For the region as a whole, models disagree. Mostly they predict increases in mean annual rainfall and suggest a slight dry season decrease and wet season increase in precipitation (Australian Bureau of Meteorology and CSIRO 2011). However, based on statistical downscaling, (Timm and Diaz 2009) projected the most likely precipitation scenario for Hawai’i for the 21st century to be a 5% to 10% reduction for the wet season and a 5% increase in the dry season. On most islands increased temperatures coupled with decreased rainfall and increased drought will lead to an additional need for freshwater resources for drinking and crop irrigation (Döll 2002; Sivakumar and Hansen 2007). Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, limited potable water sources and agricultural resources (Barnett and Adger 2003). The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time (Keener et al. 2012). See also Key Message 4 on sea level rise in this chapter and Ch. 2: Our Changing Climate, Key Message 9).
New information and remaining uncertainties	Climate change impacts on freshwater resources in the Pacific Islands region will vary because of differing island size and height, which affect water storage capability and susceptibility to coastal inundation. The impacts will also vary because of natural phase variability (for example, ENSO, PDO) in precipitation and

	storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location. Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.
Assessment of confidence based on evidence	Freshwater systems are inherently fragile. Historical observations show strong evidence of a decreasing trend for rainfall in Hawaiʻi and many other Pacific Islands. (see also Chapter 2 in (Keener et al. 2012)). This gives us **high** confidence in the conclusion.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See KM#1.

Key message #3/5	**Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems with increasing exposure to fire and invasive species, increasing the risk of extinctions.**
Description of evidence base	In Hawai’i and the Central North Pacific (CNP) projected annual surface air temperature increases are 1.0°F-2.5°F by 2035 relative to 1971-2000 (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific (WNP) the projected increases are 2.0°F-2.3°F by 2030, 6.1°F-8.5°F by 2055, and 4.9°F-9.2°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific (CSP) projected annual surface air temperature increases are 1.1°F-1.3°F by 2030, 1.8°F-2.5°F by 2055 and 2.5°F-4.9°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In Hawai’i the rate of increase has been greater at high elevations (Giambelluca et al. 2008). In Hawai’i and the Central North Pacific (CNP) projected annual surface air temperature increases are 1.0°F-2.5°F by 2035 relative to 1971-2000 (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific (WNP) the projected increases are 2.0°F-2.3°F by 2030, 3.4°F-4.7°C by 2055, and 4.9°F-9.2°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific (CSP) projected annual surface air temperature increases are 1.1°F-1.3°F by 2030, 1.8°F-2.5°F by 2055 and 2.5°F-4.9°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In Hawai’i mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high ENSO and PDO-related variability (Bassiouni and Oki 2012; Chu and Chen 2005; Frazier et al. 2011; Oki 2004). Based on statistical downscaling, (Timm and Diaz 2009) projected the most likely precipitation scenario for Hawai’i for the 21st century to be a 5%-10% reduction for the wet season and a 5% increase in the dry season. On high islands like Hawai‘i, decreases in precipitation and base flow (Oki 2004) are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and water-intensive sectors such as agriculture and tourism. Hawai‘ian high-elevation alpine ecosystems on Hawai‘i and Maui islands are already beginning to show strong signs of increased drought and warmer temperatures (Cao et al. 2007). Demographic data for the Haleakalā silversword, a unique (endemic to upper Haleakalā volcano) and integral component of the alpine ecosystem in Haleakalā National Park, Maui, have recorded a severe decline in plant numbers over the past two decades (Krushelnycky et al. 2012). Many of Hawai‘i’s endemic forest birds, marvels of evolution largely limited to high-elevation forests by predation and disease, are increasingly vulnerable as rising temperatures allow the disease-vectoring mosquitoes to thrive upslope and thereby reduce the extent of safe bird habitat (Benning et al. 2002; LaPointe et al. 2012).
New information and remaining uncertainties	Climate change impacts in the Pacific Islands region will vary because of differing island size and height. The impacts will also vary because of natural phase variability (for example, ENSO, PDO) in precipitation and storminess (tropical and extra-tropical storms) as well as long term trends, both strongly influenced by geographic location. Climate model simulations produce conflicting assessments as to how the tropical

	Pacific atmospheric circulation will respond in the future to climate change. Climate change ecosystem response is poorly understood.
Assessment of confidence based on evidence	Terrestrial ecosystems are already showing signs of stress. Historical observations show strong evidence of a decreasing trend for rainfall in Hawaiʻi and many other Pacific Islands (Keener et al. 2012). Confidence is therefore **high** in this key message.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 23: Hawai‘i and Pacific Islands

Key Message Process: See KM#1.

Key message #4/5	**Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.**
Description of evidence base	Evidence for sea level rise across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Message 9) and its Traceable Accounts. All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. In addition, numerous recent studies (Keener et al. 2012) find realistic much higher sea level-rise projections than what the IPCC reported in 2007 (IPCC 2007) for the rest of this century. (See also Ch. 2: Our Changing Climate, Key Message 9). Sea level is rising and is expected to continue to rise. Over the past few decades, global mean sea level as measured by satellite altimetry has been rising at an average rate of twice the estimated rate for the 20th century based on tide gauge measurements (Nerem et al. 2010), with models suggesting that global sea level will rise significantly over the course of this century. Regionally, the highest increases occurring in the WNP (Becker et al. 2012; Timmermann et al. 2010). However, the current regional rates are not expected to persist, as sea level will fall in response to a change in phase of natural variability (Marra et al. 2012). Regional trend variations in sea level at interannual and interdecadal time scales generally are attributed to changes in prevailing wind patterns associated with ENSO as well as the PDO and low frequency components of the Southern Oscillation Index (SOI) (Merrifield and Maltrud 2011; Merrifield et al. 2012; Meyssignac et al. 2012).On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable (Marra et al. 2012). Agricultural activity will also be affected, as sea level rise decreases the land area available for farming (Easterling et al. 2007) and episodic inundation increases salinity of groundwater resources. Impacts to the built environment on low-lying portions of high islands will be much the same as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. In Waikīkī Improvement Association. (Waikīkī Improvement Association 2008) “Our analyses estimate that nearly $2.0 billion in overall visitor expenditures could be lost annually due to a complete erosion of Waikīkī Beach.” Coastal and near shore environments (sandy beaches, shallow coral reefs, seagrass beds, intertidal flats and mangrove forests) and the vegetation and terrestrial animals in these systems will progressively be affected as sea level rise and high wave events alter atoll island size and shape and reduce habitat features necessary for survival. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10%–20% of in total regional mangrove area over the next century. (Gilman et al. 2008). Also, atoll-breeding Pacific seabirds will lose large segments of their breeding populations (Arata et al. 2009) as their habitat is increasingly and more extensively inundated.
Major uncertainties	Regional trend variations in sea level at interannual and interdecadal time scales generally are attributed to changes in prevailing wind patterns associated with ENSO as well as the PDO and low frequency components of the Southern Oscillation Index (SOI). Regionally, sea level will continue to rise with global sea level. However, the current regional rates are not expected to persist, as sea level will fall in response to

	a change in phase of natural variability.
Assessment of confidence based on evidence	Strong evidence for sea level rise (Keener et al. 2012) (see also Ch. 25: Coastal Zone and Ch. 2: Our Changing Climate). Confidence is therefore **very high**. For other aspects of the key message concerning impacts, confidence is **high**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 23: Hawai'i and Pacific Islands

Key Message Process: See KM#1.

Key message #5/5	**Mounting threats to food and water security, infrastructure, and public health and safety will lead to increasing human migration from low to high elevation islands and continental sites. It will become increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.**
Description of evidence base	Climate changes threats to communities, cultures, and ecosystems of the Pacific Islands both directly through their impact on food and water security, for example, as well indirectly through their impact on economic sectors including fisheries and tourism. On most islands, increased temperatures coupled with decreased rainfall and increased drought will lead to an additional need for freshwater resources for drinking and crop irrigation (Döll 2002; Sivakumar and Hansen 2007). This is particularly important for locations in the tropics and subtropics where observed data and model projections suggest that the average growing season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006 by the end of the 21st century. Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, limited potable water sources and agricultural resources (Barnett and Adger 2003). The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time. These are but part of a cascade of impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities (Storlazzi et al. 2011) . On high islands like Hawai'i, decreases in precipitation and base flow (Oki 2004) are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and water-intensive sectors such as agriculture and tourism. Increasing mean oceanic and coastal water levels and the possibility of more frequent extreme water level events with flooding and erosion, will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, waste water systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location depending on how natural sea level variability combines with modest increases of mean levels (Keener et al. 2012). On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming (Easterling et al. 2007) and episodic inundation increases salinity of groundwater resources. With respect to cultural resources, impacts will extend from the loss of tangible artifacts and structures (Vitousek et al. 2004) to the intangible loss of a land base and the cultural traditions that are associated with it (Henry and Jeffery 2008).
New information and remaining uncertainties	Whenever appraising threats to human society, it is uncertain the degree to which societies will successfully adapt to limit impact. For island communities though, the ability to migrate is very limited, and especially to adapt when long-standing cultural issues cannot readily be altered.
Assessment of confidence based on evidence	Evidence for climate change and impacts is strong, but highly variable for location to location, yet one can be highly confident that climate change will continue to pose varied threats in the region. Adaptive capacity is also highly variable among the islands, so the resulting situation will play out differently in different places. Confidence is therefore **medium**.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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24. Oceans and Marine Resources

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Key Messages

1. **The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.**
2. **The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.**
3. **Significant habitat loss will continue to occur due to climate change, in particular for Arctic and coral reef ecosystems, while expansions of habitat in other areas and for other species will occur. These changes will consequently alter the distribution, abundance, and productivity of many marine species.**
4. **Rising sea surface temperatures have been linked with increasing levels and ranges of diseases of humans and marine life, such as corals, abalones, oysters, fishes, and marine mammals.**
5. **Altered environmental conditions due to climate change will affect, in both positive and negative ways, human uses of the ocean, including transportation, resource use and extraction, leisure and tourism activities and industries, in nearshore and offshore areas. Many marine activities are designed based on historical conditions. Thus, climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.**
6. **In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate-change impacts. These initiatives, such as increasing the resilience of built infrastructure or natural marine ecosystems, can serve as a model for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.**

As a nation, we depend on the oceans for seafood, recreation and tourism, cultural heritage, transportation of goods, and, increasingly, energy and other critical resources. The U.S. Exclusive Economic Zone extends 200 nautical miles seaward from the coasts, spanning an area about 1.7 times the land area of the continental U.S. and encompassing waters along the U.S. East, West, and Gulf coasts, around Alaska and Hawaii, and including the U.S. territories in the Pacific and Caribbean. This vast region is host to a rich diversity of marine plants and animals and a wide range of ecosystems, from tropical coral reefs to sea ice-covered polar waters in the Arctic.

Oceans support vibrant economies and coastal communities with numerous businesses and jobs. More than 160 million people live in the coastal watershed counties of the U.S., and population in this zone is expected to grow in the future. The oceans help regulate climate, absorb carbon dioxide (an important greenhouse, or heat-trapping, gas), and strongly influence weather patterns far into the continental interior. Ocean issues touch all of us in direct and indirect ways (NMFS 2011; NOC 2012; NRC 2010b; U.S.Commission on Ocean Policy 2004).

Changing climate conditions are already affecting these valuable marine ecosystems and the array of resources and services we derive from the sea. Some climate trends, such as rising seawater temperatures and ocean acidification, are common across much of the coastal areas and open ocean worldwide. The biological responses to climate change often vary from region to region, depending on the different combinations of species, habitats, and other attributes of local systems. Data records for the ocean are often shorter and less complete than those on land, and in many cases it is still difficult to discern long-term ocean trends from natural variability (Doney et al. 2012).

Rising Ocean Temperatures

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Cores from corals, and other indirect temperature measurements, indicate the recent rapid increase of ocean temperature is the greatest that has occurred in at least the past millennium and can only be reproduced by climate models with the inclusion of manmade sources of heat-trapping gas emissions (Jansen et al. 2007; Jungclaus et al. 2010; Mann et al. 2008; Oppo et al. 2009). The ocean is a critical reservoir for heat within Earth's climate system, and because of seawater's large heat capacity, small changes in ocean temperature reflect large changes in ocean heat storage. Direct measurement of ocean temperatures shows warming beginning in about 1970 down to at least 2300 feet, with stronger warming near the surface leading to increased thermal stratification of the water column (Levitus et al. 2009; Levitus et al. 2012). Sea surface temperatures in the North Atlantic and Pacific, including near U.S. coasts, have also increased since 1900 (Deser et al. 2010; Smith et al. 2008). In conjunction with a warming climate, the extent and thickness of Arctic sea ice has decreased rapidly over the past four decades (Comiso 2011; Rothrock et al. 2008; Walsh and Chapman 2001). Models that best match historical trends project seasonally ice-free northern waters by the 2030s (Stroeve et al. 2007; Stroeve et al. 2012; Wang and Overland 2012).

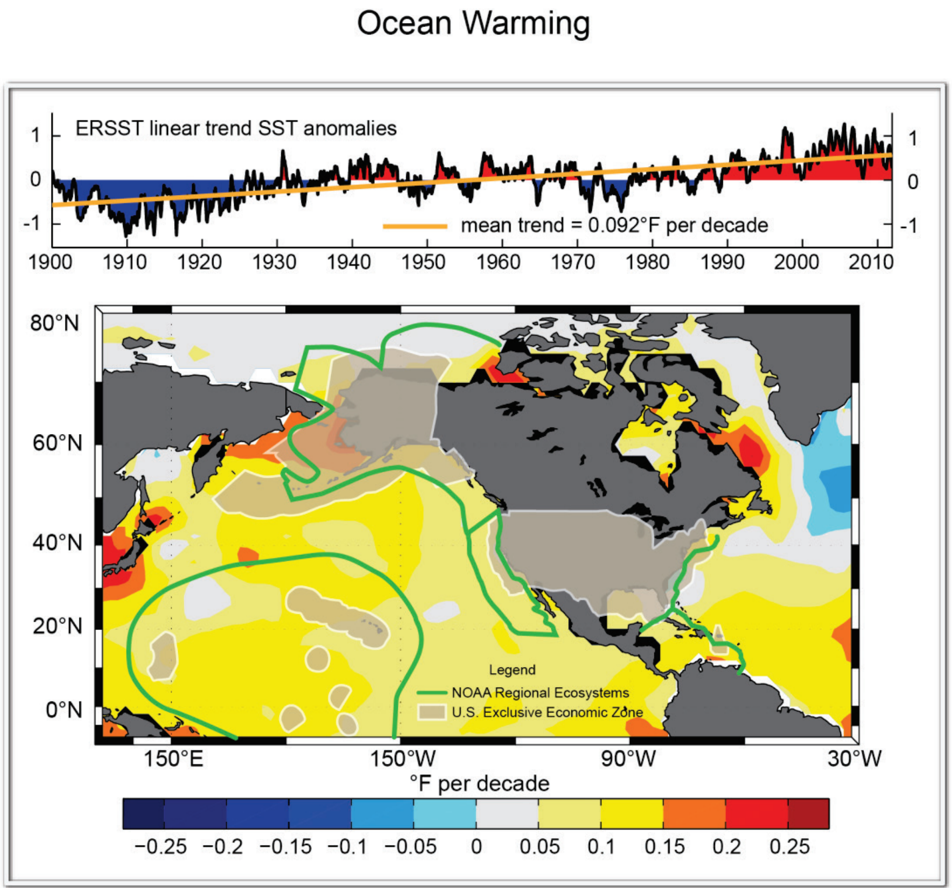

Figure 24.1: Ocean Warming

Caption: The average sea surface temperature (SST, upper panel) for the ocean surrounding the U.S. and its territories (the area covered by the map in the lower panel) has increased by more than 0.9°F over the past century. There is significant variation from place to place, with the ocean off the coast of Alaska, for example, warming far more rapidly than other areas (lower panel). The shading on the map denotes U.S. land territory and the regions where the U.S. has rights over the exploration and use of marine resources, as defined by the U.S. Exclusive Economic Zone (EEZ). Green lines denote the boundaries of the National Oceanic and Atmospheric Administration (NOAA) Regional Ecosystems, which often extend beyond the EEZ. Warming of the upper ocean is reducing the biological productivity of tropical and subtropical (poleward of the tropics) oceans. This can affect the food web, resulting in changes for fisheries and other important human activities that depend on ocean productivity. Adapted from (Chavez et al. 2011).

Climate-driven warming reduces vertical mixing that brings nutrients up from deeper water with potential impacts on biological productivity. Warming and altered ocean circulation are also expected to reduce the supply of oxygen to deeper waters, leading to expected future expansion of sub-surface low-oxygen zones (Keeling et al. 2010; Stramma et al. 2008). Both reduced nutrients at the surface and reduced oxygen at depth have the potential to change ocean productivity (Chavez et al. 2011). Satellite observations indicate that warming of the upper ocean leads to reductions in the biological productivity of tropical and subtropical (poleward of the tropics) oceans and expansion of the area of surface waters with very low plankton biomass (Behrenfeld et al. 2006; Polovina et al. 2008). Ecosystem models suggest that the same patterns of change will occur due to surface warming over this century, perhaps also increasing productivity near the poles (Polovina et al. 2011; Steinacher et al. 2010). These changes can affect ecosystems at multiple levels of the food web, with consequent changes for fisheries and other important human activities that depend on ocean productivity (Doney et al. 2012; Sumaila et al. 2011).

Other changes in the physical and chemical properties of the ocean are also underway due to climate change. These include rising sea level (Church and White 2011a), changes in upper ocean salinity (including reduced salinity of Arctic surface waters) resulting from changed inputs of freshwater and losses from evaporation, increases in wave height from changes in wind speed, and changes in oxygen content at various depths – changes that will affect marine ecosystems and human uses of the ocean in the coming years (Doney et al. 2012).

Ocean Impacts of Increased Atmospheric Carbon Dioxide

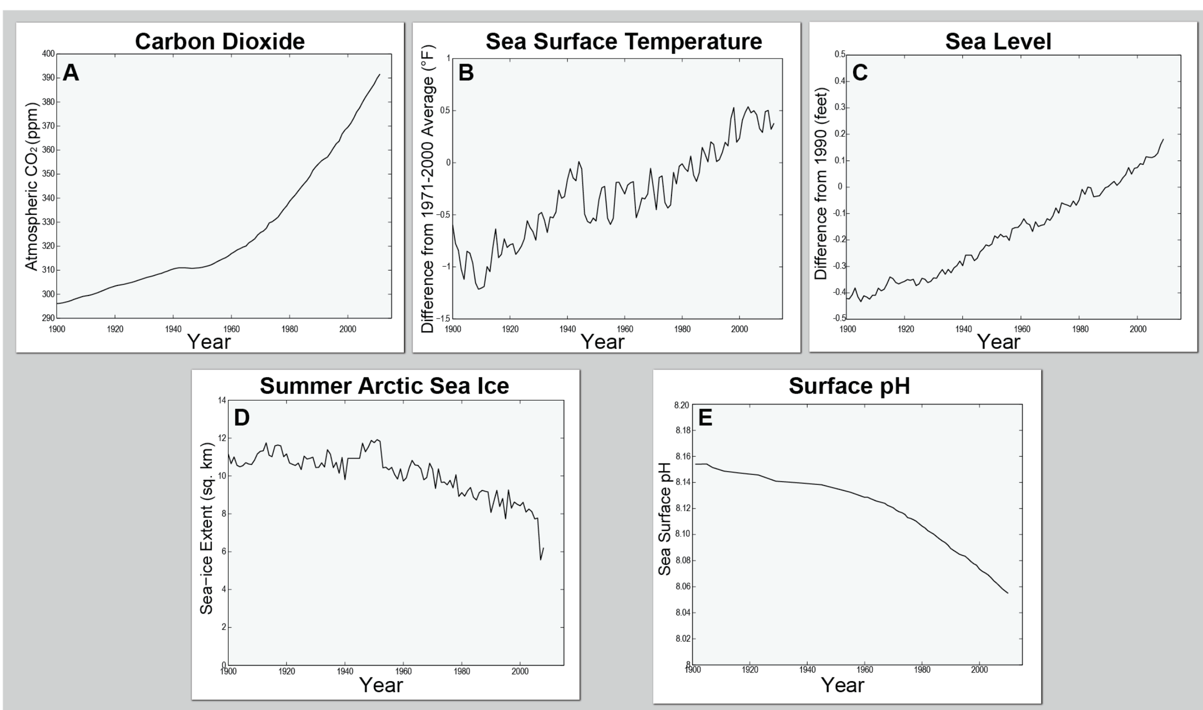

Figure 24.2: Ocean Impacts of Increased Atmospheric Carbon Dioxide

Caption: As heat-trapping gases, primarily carbon dioxide (CO_2) (panel A), have increased over the past decades, not only has air temperature increased worldwide, but so has the temperature of the surface ocean (panel B). The increased ocean temperature, combined with melting of glaciers and ice sheets on land, is leading to higher sea levels (panel C). Increased air and ocean temperatures are also causing the continued, dramatic decline in Arctic sea ice during the summer (panel D). In addition to these climate effects of increased CO_2, the ocean is becoming more acidic as increased atmospheric CO_2 dissolves into the ocean (panel E). (Sources: Adapted from SST: CSIRO 2012; NCDC 2012; Smith et al. 2008) CO_2: (Etheridge 2010; Tans and Keeling 2012), and NOAA NCDC, SLR: (CSIRO 2012) and(Church and White 2011) , pH: (Doney et al. 2012), and Sea Ice: (University of Illinois 2012)

While the global pattern is clear, there is considerable variability in regional and local manifestation of the effects of climate change, because oceanographic conditions are not uniform and are strongly influenced by natural climate fluctuations. Interactions with processes in the atmosphere and on land, such as rainfall patterns and runoff, also vary by region and are strongly influenced by natural climate fluctuations, resulting in additional local variation in the observed effects in the ocean.

Ocean Acidification Alters Marine Ecosystems

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Atmospheric CO_2 has risen by about 40% above preindustrial levels (MacFarling Meure et al. 2006; Tans and Keeling 2012). The ocean absorbs some of the human-caused emissions of carbon dioxide, thereby changing seawater chemistry, decreasing pH (that is, making seawater more acidic) (NRC 2010b; Sabine et al. 1999) (see also Ch. 2: Our Changing Climate, Key Message 11). Regional differences in ocean pH occur as a result of variability in other regional or local conditions as noted above (Feely et al. 2008). Ocean acidification will continue in the future due to the basic physics of the interaction of atmospheric carbon dioxide and ocean water. More acidic waters create repercussions along the marine food chain. For example, calcium carbonate is a skeletal component of a wide variety of organisms in the oceans, including corals. Decreased seawater pH makes it more difficult for these living things to form and maintain calcium carbonate shells and skeletal components, resulting in alterations in marine ecosystems that will become more severe as present-day trends in acidification continue or accelerate (Cooley et al. 2009; Doney et al. 2009; Riebesell et al. 2007). Tropical corals may be particularly susceptible to the combination of ocean acidification and ocean warming, which would threaten the rich and biologically diverse coral reef habitats.

Ocean Acidification Causes Clams to Shrink

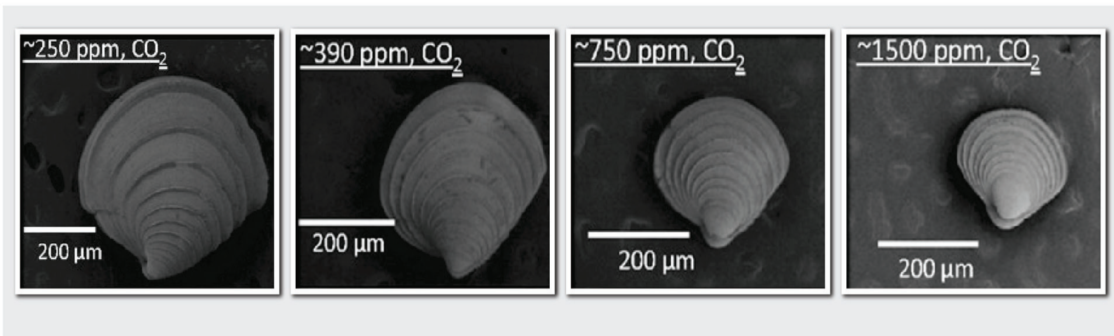

Figure 24.3: Ocean Acidification Causes Clams to Shrink

Caption: The 36-day-old clams in the photos are a single species, *Mercenaria mercenaria*, grown under varying levels of carbon dioxide (CO_2) in the air. CO_2 is absorbed from the air by ocean water, acidifying the water and thus reducing the ability of the clam to grow its shell. As seen in the photos, the clams (measured in microns) become progressively smaller as CO_2 levels rise. Current atmospheric CO_2 concentration is approximately 390 parts per million, which is the level in the second photo from the left, showing that these commercially important animals have already been affected by changes in CO_2 levels since the preindustrial era, when concentration was about 250 parts per million. (Figure source: Talmage and Gobler 2010)

Eighty percent of seafood consumed in the U.S. is imported, and more than half of the imported seafood comes from aquaculture (fish and shellfish farming) (NMFS 2011). Increased ocean acidification, low-oxygen events, and rising temperatures are already affecting shellfish aquaculture operations. Higher temperatures are predicted to increase aquaculture potential in poleward regions, but decrease it in the tropics (De Silva and Soto 2009). Acidification, however, will likely reduce growth and survival of shellfish stocks in all regions (Doney et al. 2009).

Box: The Impacts of Ocean Acidification on the West Coast Aquaculture Industry

Ocean acidification has already changed the way shellfish farmers on the West Coast conduct business. For oyster growers, the practical effect of the lowering pH of ocean water has not only been to make the water more acidic, but also more corrosive to young shellfish raised in aquaculture facilities. Growers at Whiskey Creek Hatchery, located in Oregon’s Netarts Bay, found that low pH seawater during spawning reduced growth in mid-stage larval (juvenile) Pacific oysters (Barton et al. 2012). Hatcheries in Washington State have also experienced losses of spat (oyster larvae that have attached to a surface and begun to develop a shell) due to water quality issues that include other human-caused effects like dredging and pollution (Feely et al. 2010). Facilities like the Taylor Shellfish Farms hatchery on Hood Canal have changed their production techniques to respond to increasing acidification in Puget Sound.

These impacts highlight two changing aspects in regional ocean chemistry: 1) existing natural variation may interact with human-caused change to produce unanticipated results for shell-forming marine life, especially in coastal regions (Waldbusser et al. 2011); and 2) as a result, there is an increasing need for information about water chemistry conditions through the use of sensor networks. In the case of Whiskey Creek, instruments installed in collaboration with ocean scientists created an "early warning" system that allows oyster growers to choose the time they take water into the hatchery from the coast. This allows them to avoid the lower-pH water related to upwelling and the commensurate loss of productivity in the hatchery.

From a biological perspective, these kinds of preventative measures can help produce higher-quality oysters. Studies on native Olympia oysters (*Ostrea lurida*) show that there is a "carry-over" effect of acidified water – oysters exposed to low pH conditions while juveniles continue to grow slower in later life stages (Hettinger et al. in press). Research on some oysters species such as Pacific oyster (*Crassostrea gigas*), the commercially important species in U.S. west coast aquaculture, shows that specially selected strains can be more resistant to acidification (Parker et al. 2012).

Overall, economically important species such as oysters, mussels, and sea urchins are highly vulnerable to changes in ocean conditions brought on by climate change. Sea temperature and acidification are expected to increase; the acidity of surface seawater is projected to increase by almost a factor of two by the end of this century. Some important cultured species may all be influenced in developing stages, during fertilization, and as adults (Gibson et al. 2011), resulting in lower productivity. Action groups, such as the California Current Acidification Network (C-CAN), are working to address the needs of the shellfish industry – both wild and aquaculture-based fisheries – in the face of ocean change. These efforts bring scientists from across disciplines together with aquaculturists, fishermen, the "ocean observing" community, and state and federal decision-makers to ensure a concerted, standardized, and cost-effective approach to gaining new understanding of the impact of acidification on ecosystems and the economy.

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Habitat Loss Affects Marine Life

Significant habitat loss will continue to occur due to climate change, in particular for Arctic and coral reef ecosystems, while expansions of habitat in other areas and for other species will occur. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Species have responded to climate change in part by shifting where they live (Chen et al. 2011; Parmesan 2006). Such range shifts result in ecosystem changes, including the relationships between species and their connection to habitat, because different species adapt to changing conditions in different ways. This means that ocean ecosystems are changing in complex ways, with accompanying changes in ecosystem functions (such as nutrient cycling, productivity of species, and predator-prey relationships). Overall habitat extent is expected to change as well, though the degree of range migration will depend upon the life history of particular species. For example, reduction in seasonal sea ice cover and warmer surface temperatures may open up new habitat in polar regions for some important fish species, such as cod, herring, and pollock (Loeng et al. 2005) However, continued presence of cold bottom-water temperatures on the Alaskan Continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea

(Sigler et al. 2011). In addition, warming may cause reductions in the abundances of some species, such as pollock, in the their current ranges in the Bering Sea (Mueter et al. 2011). For other ice-dependent species, including several marine mammals such as polar bears and harp seals, the loss of their critical habitat will result in population declines (Moore and Huntington 2008; Wassmann 2011). These changes will result in changing interactions among species with consequences that are difficult to predict.

Climate-change impacts such as ocean temperature increases can profoundly affect production of natural stocks of fish by changing growth, reproduction, survival, and other critical characteristics of fish stocks and ecosystems. Fish stocks are moving poleward and to deeper water (Dulvy et al. 2008; Mueter and Litzow 2008; Murawski 1993; Nye et al. 2009; Perry et al. 2005), and productivity of fisheries is predicted to decline in the lower 48 states, while increasing in parts of Alaska (Cheung et al. 2009). Costs of fishing are predicted to increase as fisheries transition to new species and as processing plants and fishing jobs shift poleward (Sumaila et al. 2011). The cumulative impact of such changes will be highly variable on regional scales because of the combination of factors – some acting in opposite directions. Some areas will benefit from range expansions of valuable species or increases in productivity, while others will suffer as species move away from previously productive areas.

Coral Reef Ecosystem Collapse

Recent research indicates that 75% of the world's coral reefs are threatened due to the interactive effects of climate change and local sources of stress, such as overfishing, nutrient pollution, and disease (Burke et al. 2011; Dudgeon et al. 2010; Hoegh-Guldberg et al. 2007; Hughes et al. 2010). In Florida, all reefs are rated as threatened, with significant impacts on valuable ecosystem services they provide (Mumby and Steneck 2011). Caribbean coral cover has decreased from 50% to only 10%, an 80% reduction, in less than three decades (Gardner et al. 2003). These declines have in turn led to a flattening of the three dimensional structure and a decrease in the capacity of coral reefs to provide shelter and other resources for other reef-dependent species of fish and invertebrates (Alvarez-Filip et al. 2009).

The symbiosis between coral and its associated algae partner is destroyed by higher than usual temperatures and results in a condition where the coral is still alive, but devoid of all its color (bleaching). Bleached corals can later die or become infected with disease (Miller et al. 2009; Weil et al. 2009). Thus high temperature events alone can kill large stretches of coral reef. Evidence suggests that relatively pristine reefs with fewer human impacts and intact fish and associated invertebrates are more resilient to coral bleaching and disease (Sandin et al. 2008).

Figure 24.4: Warming Seas Are a Double-blow to Corals

Caption: A colony of star coral (*Montastraea faveolata)* off the southwest coast of Puerto Rico, estimated to be about 500 years old, exemplifies the effect of rising water temperatures. Increasing diseases due to warming waters (A) were followed by such high temperatures that bleaching, or loss of symbiotic micro-algae from coral occurred (B), followed by more disease (C) that finally killed the colony (D). (Photo credit: Ernesto Weil)

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Rising Temperatures Linked to Diseases

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases of humans and marine life, such as corals, abalones, oysters, fishes, and marine mammals.

There has been a significant increase in reported incidences of disease in corals, urchins, mollusks, marine mammals, turtles, and echinoderms over the last several decades (Ward and Lafferty 2004). The complexity of the host/environment/pathogen interaction makes it challenging to separate climate warming from the myriad of other causes facilitating increased diseased outbreaks in the ocean. However, three categories of disease-causing pathogens are unequivocally related with warming oceans.

Firstly, warmer winters due to climate change can increase the overwinter survival and growth rates of pathogens (Harvell et al. 2009). A disease-causing parasite in oysters that proliferates at high water temperatures and high salinities has spread northward up the eastern seaboard as water temperatures warmed during the 1990s (Cook et al. 1998; Ford 1996). Growth rates of coral-disease lesions increased with winter and summer warming from 1996-2006 (Weil et al. 2009). Winter warming in the Arctic is resulting in increased incidence of a salmon disease in the Bering Sea, and is now thought to be a cause of a 57% decline of Yukon Chinook salmon (Zuray et al. 2012).

Secondly, increasing disease outbreaks of ecologically important species like coral, eelgrass, and abalone have been linked spatially with rising temperature anomalies. The spectacular biodiversity of tropical coral reefs is particularly vulnerable to warming, because the corals that form the foundational reef structure live very near their upper thermal limits. The increasing frequency of record hot temperatures has caused widespread coral bleaching (Eakin et al. 2010) and disease outbreaks (Bruno et al. 2007)), and is a principle factor contributing to the endangered status of a third of the world's reef-building corals (Carpenter et al. 2008). In the Chesapeake Bay, eelgrass died out almost completely during the record-hot summers of 2005 and 2010 (Moore and Jarvis 2008), and the California black abalone has been driven to the edge of extinction by a combination of warming water and a bacterial disease (Altstatt et al. 1996; Neumann et al. 2010).

Thirdly, there is evidence that increased water temperature is responsible for the enhanced survival and growth of certain marine bacteria that make humans sick (Baker-Austin et al. 2012). Warm seasonal expansion of *Vibrio parahaemolyticus*, a pathogenic bacterial species, is responsible for human illnesses associated with oysters harvested from the Gulf of Mexico (Martinez-Urtaza et al. 2010) and northern Europe (Baker-Austin et al. 2012). *Vibrio vulnificus*, which is responsible for the overwhelming majority of reported seafood-related deaths in the U.S. (Oliver and Kaper 2007), is also a significant and growing source of potentially fatal wound infections associated with recreational swimming, fishing-related cuts, and seafood handling, and is most frequently found in water with a temperature above 68°F (Martinez-Urtaza et al. 2010; Oliver and Kaper 2007; Scallan et al. 2011; Weis et al. 2011).

There has also been a significant increase in reported incidences of disease in urchins, mollusks, marine mammals, turtles, and echinoderms (a group of some 70,000 marine species including sea stars, sea urchins, and sand dollars) over the last several decades (Bates et al. 2010; Bruno et al. 2007; Eakin et al. 2010; Harvell et al. 2009; Staehli et al. 2009). Increasing disease outbreaks affecting ecologically important species, which provide critical habitat for other species such as corals (Boyett et al. 2007; Bruno et al. 2007; Ward et al. 2007), algae (Case et al. 2011) and eelgrass (Hughes et al. 2002), have been linked with rising temperatures. Disease increases mortality and can reduce abundance for affected populations as well as fundamentally change ecosystems by changing habitat or species relationships. For example, loss of eelgrass beds due to disease can reduce critical nursery habitat for several species of commercially important fish (Hughes et al. 2002).

Impacts of Marine-related Climate Change

Altered environmental conditions due to climate change will affect, in both positive and negative ways, human uses of the ocean, including transportation, resource use and extraction, leisure and tourism activities and industries, in nearshore and offshore areas. Many marine activities are designed based on historical conditions. Thus, climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Climate change will affect maritime security, transportation, and governance. Recently, discussion has expanded to include the growing security, transportation, and governance dimensions of global climate change. For example, according to some researchers, the Arctic region "could slide into a new era featuring jurisdictional conflicts, increasingly severe clashes over the extraction of natural resources, and the emergence of a new 'great game' among the global powers" (Berkman and Young 2009). National security concerns and threats to national sovereignty have also been a recent focus of attention (Borgerson 2008; Campbell et al. 2007; Lackenbauer 2011). With sea ice receding in the Arctic as a result of rising temperatures, global shipping patterns are already changing and will continue to change considerably in the decades to come (Berkman and Young 2009; Cressey 2007; Khon et al. 2010; Stewart et al. 2007).

Resource use for fisheries, aquaculture, energy production, and other activities in ocean areas will also need to adjust to changing conditions. Aside from the movement of living resources, discussed above, changing ocean and weather conditions make any activities at sea that much more difficult to plan, design, and operate.

In the U.S., the tourism industry also plays a large economic role in ocean services. Nationally in 2010, 2.8% of gross domestic product, 7.52 million jobs, and $1.11 trillion in travel and recreational total sales are supported by tourism (OTTI 2011a, 2011b). In addition, in 2009-2010, nine of the top ten states and U.S. territories and seven of the top ten cities visited by overseas travelers were coastal, including the Great Lakes (OTTI 2011a, 2011b). Changes in the location and distribution of marine resources such as fish, healthy reefs, and marine mammals due to climate change will affect the recreational industries and all people that depend on reliable access to these resources in predictable locales. For example, as fish species shift poleward or to deeper waters (Cheung et al. 2011; Nye et al. 2009), these fish may be less accessible to recreational fishermen. Similarly, new weather conditions differing from the historical pattern, and extreme events such as typhoons and hurricanes, mean that the public will not be able to count on recent experience in planning leisure and tourism activities (Moreno and Becken 2009; Scott et al. 2004; Yu et al. 2009). Climate impacts such as changes in wind patterns and wave heights, and more intense storm events will pose a challenge for tourism, boating, recreational fishing, diving, and snorkeling, all of which rely on highly predictable comfortable water and air temperatures and calm waters (Moreno and Becken 2009; Scott et al. 2004). As weather patterns change, and air and sea surface temperatures rise, preferred locations for recreation and tourism also may change. In addition, infrastructure such as marinas, marine supply stores, boardwalks, hotels, and restaurants that support leisure activities and tourism will be negatively affected by sea level rise. They may also be impacted by increased storm intensity, changing wave heights

(Scott et al. 2004; Yu et al. 2009), and other expected effects of a changing climate; these impacts will vary significantly by region (IPCC 2012).

Initiatives Serve as a Model

In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate-change impacts. These initiatives, such as increasing the resilience of built infrastructure or natural marine ecosystems, can serve as a model for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Climate considerations can be integrated into planning, restoration, design of marine protected areas, fisheries management, and aquaculture practices to enhance ocean resilience and adaptive capacity. Many existing sustainable-use strategies, such as ending overfishing, establishing protected areas, and conserving habitat, are known to increase resilience. Analyses of fishery management and climate scenarios suggest that adjustments to harvest regimes (especially reducing harvest rates of over-exploited species) can improve catch stability under more uncertain and changing climate conditions. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years (Eide 2008; Ianelli et al. 2011; Perry et al. 2010). The stability of international ocean and fisheries treaties, particularly those covering commercially exploited and critical species, might be threatened as the ocean changes (Garcia and Rosenberg 2010).

New 5-year strategies for addressing flooding, shoreline erosion, and coastal storms have been developed by most coastal states under their Coastal Zone Management Act programs (NRC 2010a). Many of these plans are explicitly taking into account future climate scenarios as part of their adaptation initiatives. The North Pacific Fishery Management Council and NOAA have chosen to delay opening the U.S. fisheries in the Arctic Sea pending greater understanding of the changing productivity of these potential fishing grounds as they become increasingly ice-free. Private shellfish aquaculture operations are changing their business plans to adapt to ocean acidification (Barton et al. 2012; Feely et al. 2010). These changes include monitoring and altering the timing of spat settlement dependent on climate change induced conditions, as well as seeking alternative, acid-resistant strains for culturing.

Additionally, there is promise in using restoration of key habitats to provide a broad suite of benefits that can reduce climate impacts, with relatively little ongoing maintenance costs. For example, if in addition to sea level rise, an oyster reef or mangrove restoration strategy also included fish habitat benefits for commercial and recreational uses and coastal protection services, the benefits to surrounding communities could multiply quickly. Coral-reef-based tourism can be more resilient to climate change impacts through protection and restoration, as well as reduction of pollution and other habitat-destroying activities. Developing alternative livelihood options as part of adaptation strategies for marine food producing sectors can help reduce economic and social impacts of a changing climate.

Box: Climate Impacts on New England Fisheries

Fishing in New England has been associated with bottom-dwelling fish for more than 400 years, and is a central part of the region's cultural identity and social fabric. Atlantic halibut, cod, haddock, flounders, hakes, pollock, plaice, and soles are included under the term "groundfish." The fishery is pursued by both small boats (less than 50 feet long) that are typically at sea for less than a day, and by large boats (longer than 50 feet) that fish for a day to a week at a time. These vessels use home ports in more than 100 coastal communities from Maine to New Jersey and land more than $700 million in fish and shellfish at the dock each year (NOAA NMFS 2009). Captains and crew are often second- or third-generation fishermen who have learned the trade from their families.

From 1982-2006, sea surface temperature in the coastal waters of the Northeast warmed by close to twice the global rate of warming over this period (Belkin 2009). Long-term monitoring of bottom-dwelling fish communities in New England revealed that the abundance of warm-water species increased, while cool-water species decreased (Collie 2008; Nye et al. 2009). A recent study suggests that many species in this community have shifted their geographic distributions northwards by up to 200 miles since 1968, though substantial variability among species also exists (Nye et al. 2009). The northward shifts of these species are reflected in the fishery as well: landings and landed value of these species have shifted towards northern states such as Massachusetts and Maine, while southern states have seen declines.

The economic and social impacts of these changes depend in large part on the response of the fishing communities in the region (McCay et al. 2011). Communities have a range of strategies for coping with the inherent uncertainty and variability of fishing, including diversification among species and livelihoods, but climate change imposes both increased variability and sustained change that may push these fishermen beyond their ability to cope (Adger et al. 2009). Larger fishing boats can follow the fish to a certain extent as they shift northward, while smaller inshore boats will be more likely to leave fishing or switch to new species (Adger et al. 2009). Long-term viability of fisheries in the region may ultimately depend on a transition to new species that have shifted from regions further south (Sumaila et al. 2011).

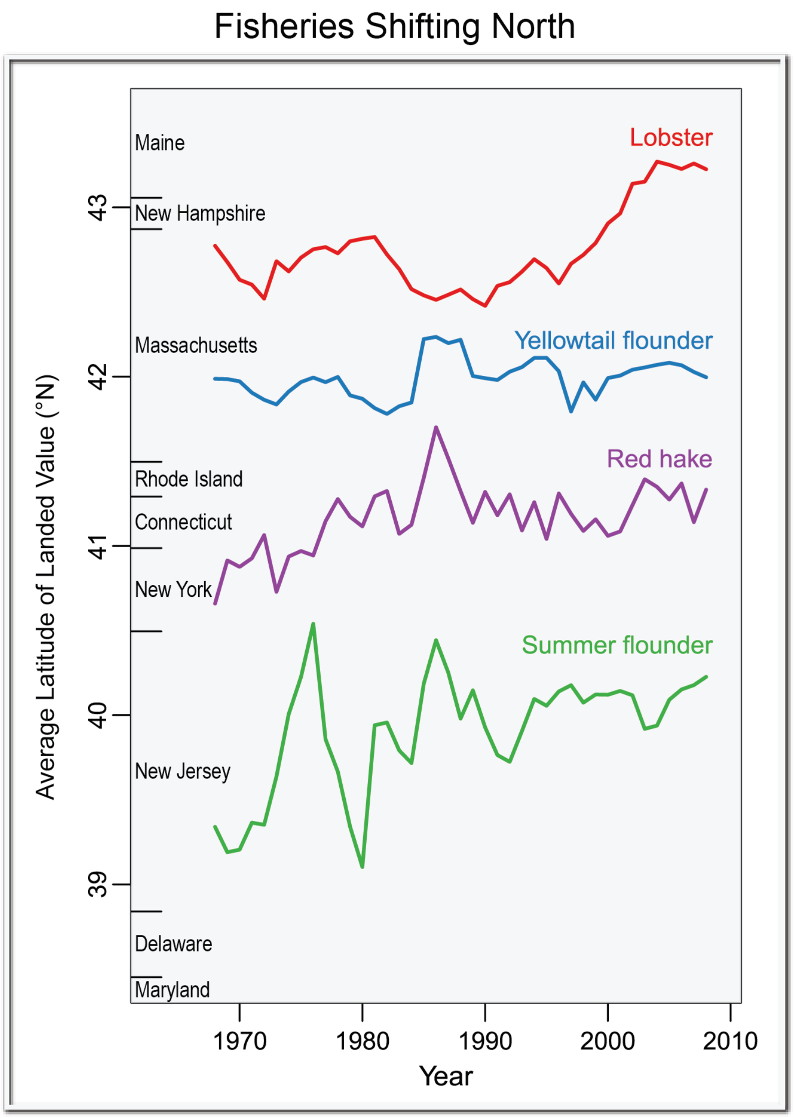

Figure 24.5: Fisheries Shifting North

Caption: Ocean species are shifting northward along U.S. coastlines as ocean temperatures have risen. As a result, over the past 40 years more northern ports have gradually increased their landings of four marine species compared to the earlier pattern of landed value. While some species move north out of an area, other species move in from the south. This kind of information can inform decisions about how to adapt to climate change. Such adaptations take time and have costs, as local knowledge and equipment are geared to the species that have long been present in an area. (Figure Source: adapted by M. Pinsky based on Griffis and Howard 2012)

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Traceable Accounts

Key Message Process: A central component of the assessment process was the Oceans and Marine Resources Climate assessment workshop that was held in January 23-24, 2012 at NOAA in Silver Springs, MD, and simultaneously, via webex, at NOAA in Seattle, WA, with nearly 30 participants participating a series of scoping presentations and breakout sessions that began the process leading to a foundational Technical Input Report (TIR) report entitled "Oceans and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment." (Griffis and Howard 2012). The report, consisting of nearly 220 pages of text organized into 7 sections with numerous subsection and more than 1200 references, was assembled by 122 authors representing a wide range of inputs including governmental agencies, NGOs, tribes and other entities.

The chapter author team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR (Griffis and Howard 2012) and of approximately 25 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team met at Conservation International in Arlington, VA on 3-4 May, 2012 for expert deliberation of draft key messages by the authors wherein each message was defended before the entire author team before this key message was selected for inclusion in the Report; these discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities".

Key message #1/6	**The rise in ocean temperature over the last century will persist into the future with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.**
Description of evidence base	The key message is supported by extensive evidence documented in Sections 2 and 3 of the Oceans Technical Input (Griffis and Howard 2012) and in the additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Relevant and recent peer-reviewed publications (Jansen et al. 2007; Jungclaus et al. 2010; Levitus et al. 2009; Levitus et al. 2012; Mann et al. 2008), including many others that are cited therein, describe evidence that ocean temperature has risen over the past century. This evidence base includes direct and indirect temperature measurements, paleoclimate records, and modeling results. There are also many relevant and recent peer-reviewed publications describing physical and chemical ocean properties that are underway due to climate change (Chavez et al. 2011; Comiso 2011; Rothrock et al. 2008).
New information and remaining uncertainties	Important new information since the last assessment includes the latest update to the Levitus et al. (2012) atlas. There is accumulating new information on all of these points with regard to physical and chemical changes in the ocean and resultant impacts on ecosystem. Both measurements and model results are continuing to sharpen the picture. A significant area of uncertain remains with regard to the region by region impacts of warming, acidification and associated changes in the oceans. Regional and local conditions mean that there is far from uniform impacts around the US coasts and internationally. Forecasting of regional changes are still an area of very active area of research though the overall patterns for some features is now clear. Large-scale and recurring climate phenomena (El Niño, the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, etc.) cause dramatic changes in biological productivity and ecosystem structure and make it difficult to discern

	climate-driven trends. Current time series of biological productivity are restricted to a handful of sites around the globe and to a few decades, and satellite time series are even shorter, beginning in 1997. Attempts to overcome these limitations suggest a decline of 1% per year over the past century have been widely debated (Chavez et al. 2011). However, the few in-situ time series mostly indicate increases in biological productivity over the past 20 years but with clear links to regional changes in climate (Chavez et al. 2011).
Assessment of confidence based on evidence	Confidence that the ocean is warming, acidifying, and sea level is rising is **very high**. Changes in other physical and chemical properties such as wave heights and oxygen minimums and salinity are of **medium** confidence. For ecosystem changes, there is **high** confidence that these are occurring, though the details of these changes are highly variable.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 24: Ocean and Marine Resources

Key Message Process: Please see KM #1 for a detailed description of process.

Key message #2/6	**The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.**
Description of evidence base	The key message is supported by extensive evidence documented in the Oceans Technical Input (Griffis and Howard 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Key message #11 in Chapter 2, Climate Change Science, and its traceable Account also provides evidence for ocean acidification. Numerous references demonstrate the declining acidity around the world (Feely et al. 2008; NRC 2010b) all confirm the recent trend. There is a rapid growth in peer-reviewed publications describing how ocean acidification will impact ecosystems (Cooley et al. 2009; Doney et al. 2009), but to date evidence is largely based on studies of calcification rather than growth, reproduction and survival of organisms. For these latter effects available evidence is from laboratory studies in low pH conditions, rather than in situ observations.
New information and remaining uncertainties	The interplay of environmental stressors may result in 'surprises' where the synergistic impacts may be more deleterious or more beneficial than expected and create complexities in terms of how to predict the outcome of the interplay of stressors on marine ecosystems. Many, but not all calcifying species, are affected in laboratory studies by increased acidity, but how those responses will cascade through ecosystems and foodwebs is still uncertain. Although studies are underway to expand understanding of ocean acidification on all aspects of organismal physiology, much remains to be learned.
Assessment of confidence based on evidence	Confidence is **very high** that carbon dioxide emissions to the atmosphere are causing ocean acidification, and high that this will alter marine ecosystems. The nature of those alterations is unclear however and predictions of most specific ecosystem changes have **low** confidence at present.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: Please see KM #1 for a detailed description of process.

Key message #3/6	**Significant habitat loss will continue to occur due to climate change, in particular for Arctic and coral reef ecosystems, while expansions of habitat in other areas and for other species will occur. These changes will consequently alter the distribution, abundance, and productivity of many marine species.**
Description of evidence base	The key message is supported by extensive evidence documented in the Oceans Technical Input (Griffis and Howard 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Many peer-reviewed publications (Burke et al. 2011; Dudgeon et al. 2010; Hoegh-Guldberg et al. 2007; Hughes et al. 2002) describe global change induced threats to coral reefs. There are also many relevant and recent peer-reviewed publications (Cheung et al. 2011; Dulvy et al. 2008; Mueter and Litzow 2008; Murawski 1993; Nye et al. 2009; Perry et al. 2005) discussing impacts of climate induced habitat change on marine species and resources.
New information and remaining uncertainties	Regional and local variation is, again a major component of the remaining uncertainties. Different areas, habitats and species are responding differently and have very different adaptive capacities. Those species that are motile will certainly respond differently, or at least at a different rate, by changing distribution and migration patterns compared to species such as corals. Although it is clear that some fish stocks are moving poleward and to deeper water, how far they will move and whether most species will move remains unclear. A key uncertainty is the extent to which various areas will benefit from range expansions of valuable species or increases in productivity, while others will suffer as species move away from previously productive areas. The loss of critical habitat due to climate change will result in changes in species interactions that are difficult to predict.
Assessment of confidence based on evidence	There is **very high** confidence that habitat and ecosystems are changing, but that change is not unidirectional by any means. Distribution, abundance, and productivity changes are species and location dependent and may be increasing or decreasing in a complex pattern.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: Please see KM #1 for a detailed description of process.

Key message #4/6	**Rising sea surface temperatures have been linked with increasing levels and ranges of diseases of humans and marine life such as corals, abalones, oysters, fishes, and marine mammals.**
Description of evidence base	The key message is supported by extensive evidence in the Oceans Technical Input (Griffis and Howard 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. As noted in the chapter, the references document increased levels and ranges of disease coincident with rising temperatures.
New information and remaining uncertainties	The complexity of the host, environment, pathogen interaction makes it challenging to separate climate warming from other causes of disease outbreaks in the ocean.
Assessment of confidence based on evidence	There is **high** confidence that disease outbreaks and levels are increasing. Again there is substantial local to regional variation but the overall pattern seems consistent.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: Please see KM #1 for a detailed description of process.

Key message #5/6	**Altered environmental conditions due to climate change will affect, in both positive and negative ways, human uses of the ocean, including transportation, resource use and extraction, leisure and tourism activities and industries, in nearshore and offshore areas. Many marine activities are designed based on historical conditions. Thus, climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.**
Description of evidence base	The key message is supported by extensive evidence documented in the Oceans Technical Input (Griffis and Howard 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Many peer-reviewed publications describe the predicted impacts of climate change on tourism and recreation industries and their associated infrastructure (Moreno and Becken 2009; Scott et al. 2004; Yu et al. 2009).
New information and remaining uncertainties	Given the complexity of leisure and tourism activities, there are large uncertainties in impacts in specific locals or for individual activities. Some businesses and communities may be able to adapt rapidly, others less so. Infrastructure impacts of climate change will also be an important part of the ability of business, communities and the public to adapt.
Assessment of confidence based on evidence	As with many other impacts of climate change, the evidence that change is occurring is very strong but the resultant impacts are still uncertain. For leisure and tourism there is suggestive evidence of changes and only **medium** confidence on the effects of the ongoing changes in ocean conditions.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 24: Ocean and Marine Resources

Key Message Process: Please see KM #1 for a detailed description of process.

Key message #6/6	**In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate-change impacts. These initiatives, such as increasing the resilience of built infrastructure or natural marine ecosystems, can serve as a model for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.**
Description of evidence base	The key message is supported by extensive evidence documented in the Oceans Technical Input (Griffis and Howard 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Scenarios suggest that adjustments to fish harvest regimes can improve catch stability under increased climate variability. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years (Eide 2008; Ianelli et al. 2011; Perry et al. 2010).
New information and remaining uncertainties	Efforts are underway to enhance the development and deployment of science in support of adaptation, to improve understanding and awareness of climate-related risks, and to enhance analytic capacity to translate understanding into planning and management activities. While critical knowledge gaps exist, there is a wealth of climate- and ocean-related science pertinent to adaptation. Including such resources as listed in the technical report.
Assessment of confidence based on evidence	There is **high** confidence that adaptation planning can help mitigate the impacts of changing ocean conditions. But there is much work to be done to craft local solutions to the set of emerging issues in ocean and coastal areas.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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25. Coastal Zone Development and Ecosystems

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Key Messages

1. **Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate-related changes.**
2. **Climate change increases exposure of nationally important assets, such as ports, tourism and fishing sites, in already-vulnerable coastal locations, threatening to disrupt economic activity beyond the coast and incurring significant costs for protecting or moving them.**
3. **Socioeconomic disparities create uneven exposures and sensitivities to coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable from coastal areas.**
4. **Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.**
5. **Growing awareness of the high vulnerability of coasts to climate change increasingly leads coastal regions to plan for potential impacts on their citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.**

U.S. Coastal Population Growth

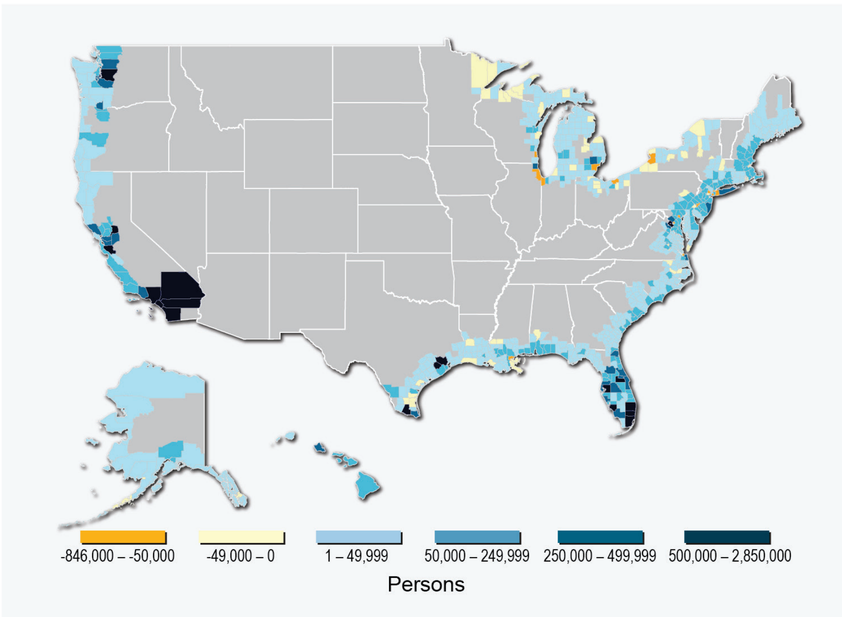


Figure 25.1: U.S. Coastal Population Growth

Caption: U.S. Coastal population growth over last 40 years (Source: U.S. Census Bureau). (Figure on projected growth to 2040 in preparation.)

Flooding During High Tides

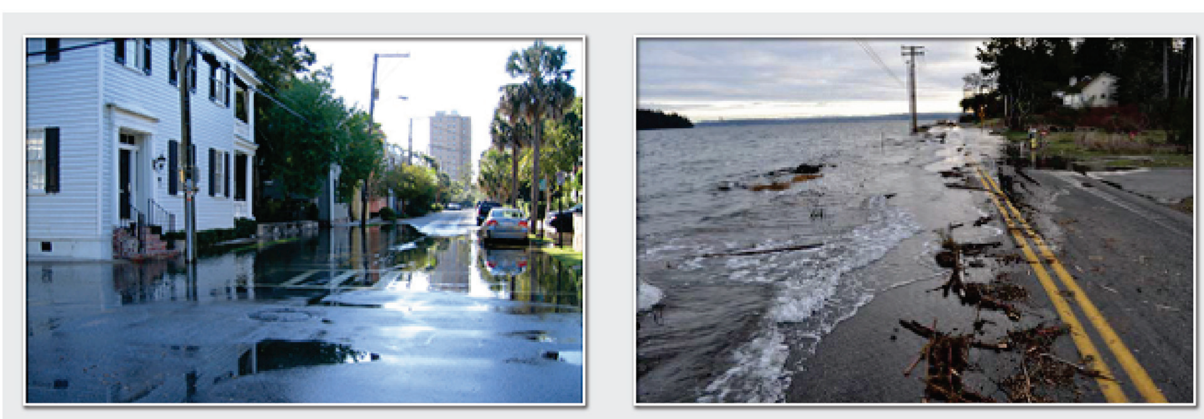


Figure 25.2: Flooding During High Tides

Caption: Sea level rise is not just a problem of the future, but is already impacting coastal communities such as Charleston, South Carolina, and Olympia Drive in South Puget Sound through flooding during high tides and impacts on coastal roads. (Sources: Left – NOAA Coastal Services Center; Right – Ray Garrido, January 6, 2010, reprinted with permission by the Washington Department of Ecology.)

Introduction

Each year, more than 1.2 million people move to the coast, adding the equivalent of nearly one San Diego or more than three Miami's to the 672 coastal counties and parishes of the U.S. As a result, 164 million – more than 50% – of Americans now live in coastal and Great Lakes watershed counties (NOAA 2011a, 2012a; U.S. Census Bureau 2010) and help generate 58% of the national GDP (NOAA 2011b). People come – and stay – for the diverse and growing employment opportunities in recreation and tourism, commerce, energy and mineral production, vibrant urban centers, and the irresistible beauty of our coasts (Bookman and Culliton 1999). Together with the millions of tourists that flock there each year, people place heavy demands on the unique natural systems and resources that make coastal areas so attractive and productive (Burkett and Davidson 2012).

Meanwhile, public agencies and officials are charged with balancing the needs of economic vitality and public safety, while sustaining the built and natural environments in the face of risks from well-known natural hazards such as storms, flooding, and erosion (NOAA 1972). Although these risks play out in different ways along the United States' more than 94,000 miles of coastline (NOAA 2012g), all coasts share one simple fact: no other area concentrates so many people and so much economic activity on so little land, so relentlessly affected by the sometimes violent interactions of land, sea, and air.

Humans have heavily altered the coastal environment through development, changes in land use, and overexploitation of resources. Now, the changing climate is imposing additional stresses (Moser et al. 2012), making life on the coast more challenging. The consequences will ripple through the entire nation, which depends on the productivity and vitality of coastal regions.

Events like "Superstorm" Sandy in 2012 have illustrated that public safety and human well-being become jeopardized by the disruption of crucial lifelines, such as water, energy, and evacuation routes. As climate continues to change, repeated disruption of lives, infrastructure functioning, and nationally and internationally important economic activities will pose intolerable burdens on those already most vulnerable, and aggravate existing impacts on valuable and irreplaceable natural systems. Planning long-term for these changes while balancing different and often competing demands are vexing challenges for decision-makers (Ch. 26: Decision Support).

Climate-related Drivers of Coastal Change

The primary climatic forces affecting the coasts are changes in temperature, sea and water levels, precipitation, storminess, and ocean acidity and circulation (Burkett and Davidson 2012).

- Sea surface temperatures are rising (IPCC 2007; Xue et al. 2012) and are expected to rise faster over the next few decades (Griffis and Howard 2012), with significant regional variation, and the possibility for more intense hurricanes as oceans warm (Emanuel et al. 2008; Grossmann and Morgan 2011; Knutson et al. 2010; Mann et al. 2007a; Mann et al. 2007b; Mendelsohn et al. 2012; Peduzzi et al. 2012; Sabbatelli and Mann 2007).

- Global mean sea levels are rising, and have been doing so for more than 100 years; higher sea levels cause more coastal erosion, more frequent flooding from higher tidal surges, and saltwater intrusion into aquifers and estuaries (Burkett and Davidson 2012; CCSP 2009b; IPCC 2007; Moser et al. 2012; Parris et al. 2012).

- Satellite observations point to an apparent increase in the rate of sea level rise since the 1990s and greater rates are expected in the future (Ch. 2: Our Changing Climate), although the exact rate remains uncertain (Anderson et al. 2010; IPCC 2007; Jevrejeva et al. 2012; Mitchum et al. 2010; Parris et al. 2012; Pfeffer et al. 2008; Rahmstorf 2007), will not be uniform along U.S. coasts (NRC 2012; Sallenger et al. 2012; Tamisiea et al. 2003; Yin et al. 2009), and can be exacerbated locally by land subsidence or reduced by uplift (Blum and Roberts 2009; Cazenave and Llovel 2010; Mazzotti et al. 2007; Nicholls and Cazenave 2010).

- Along the shorelines of the Great Lakes, lake level changes are uncertain (Ch. 18: Midwest), but erosion and sediment migration will be exacerbated by increased lakeside storm events, tributary flooding, and increased wave action due to loss of ice cover (Hayhoe et al. 2008; Uzarski et al. 2009).

- In regions where precipitation increases, coastal areas will see heavier runoff from inland areas, with the already observed trend toward more intense rainfall events continuing to increase the risk of extreme runoff and flooding. Where precipitation is expected to decline and droughts increase, freshwater inflows to the coast will be reduced (Anderson 2012; Burkett and Davidson 2012; Changnon 2009; Changnon and Westcott 2002; Hejazi and Markus 2009; IPCC 2012; Vavrus and Van Dorn 2010; Wilson and Sousounis 2000) .

- There is some observational evidence that storm tracks (for non-tropical cyclones) have shifted northward, and that the most intense tropical storms have increased in intensity in the last few decades (IPCC 2012). Future projections of storm frequency, intensity, and tracks remain uncertain (Lin et al. 2012; Mendelsohn et al. 2012; O'Gorman 2010; Rummukainen 2012; Seneviratne et al. 2012; Woollings et al. 2012).

- Carbon dioxide emitted into the atmosphere is being absorbed by the oceans, resulting in increasing ocean acidity and threatening coral reefs and shellfish (Doney et al. 2012; Hoegh-Guldberg et al. 2007). Additional threats to coastal fisheries stem from climate-related changes in oceanic circulation (Ch. 24: Ocean and Marine Resources) (Chan et al. 2008; Grantham et al. 2004).

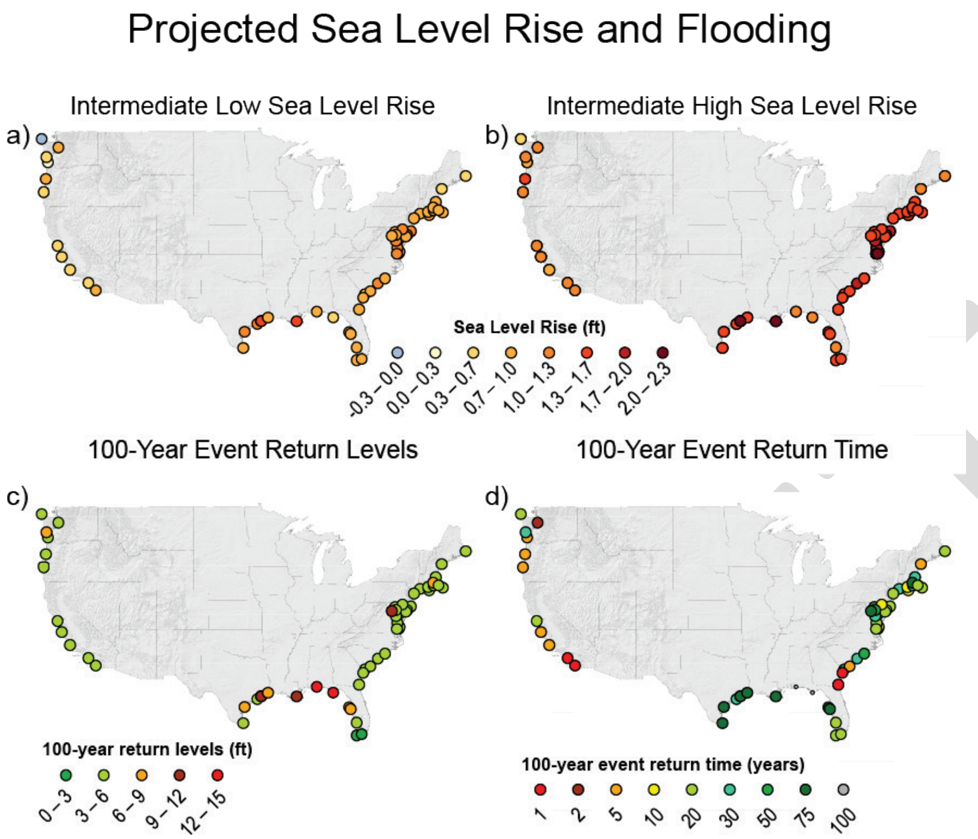


Figure 25.3: Projected Sea Level Rise and Flooding

Caption: The amount of sea level rise (SLR) will vary along different stretches of the U.S. coastline and under different SLR scenarios. The upper panels show feet of sea level above 1992 levels at different tide gauge stations based on a) a 1.6 foot SLR by 2100 and b) a 3.9 foot SLR (both within the range of 1 to 4 feet projected for 2100; Ch. 2: Our Changing Climate, Key Message 9). The amount of flooding ("return level") due to a 100-year storm (that is, a storm that has a 1% chance of occurring in any given year) is similarly projected to vary by region, as shown in panel c), which is in feet above the mean high water level during the tide gauge record (1983-2001, for most gauges).

SLR will also cause the level of flooding that occurs during today's 100-year storm to occur more frequently by mid-century, in some regions as often as once a decade or even annually, as shown in panel d). Source: Replicated Tebaldi et al. (2012) analysis with NCA sea level rise scenarios for panels a) and b); data/ensemble SLR projections used for panels c) and d) from Tebaldi et al. (2012).

None of these changes operate in isolation. The combined effects of climate changes with other human-induced stresses makes predicting the effects of climate change on coastal systems challenging. However, it is certain that these factors will create increasing hazards to the coasts' densely populated areas (Heberger et al. 2009; Strauss et al. 2012; Tebaldi et al. 2012; Weiss et al. 2011).

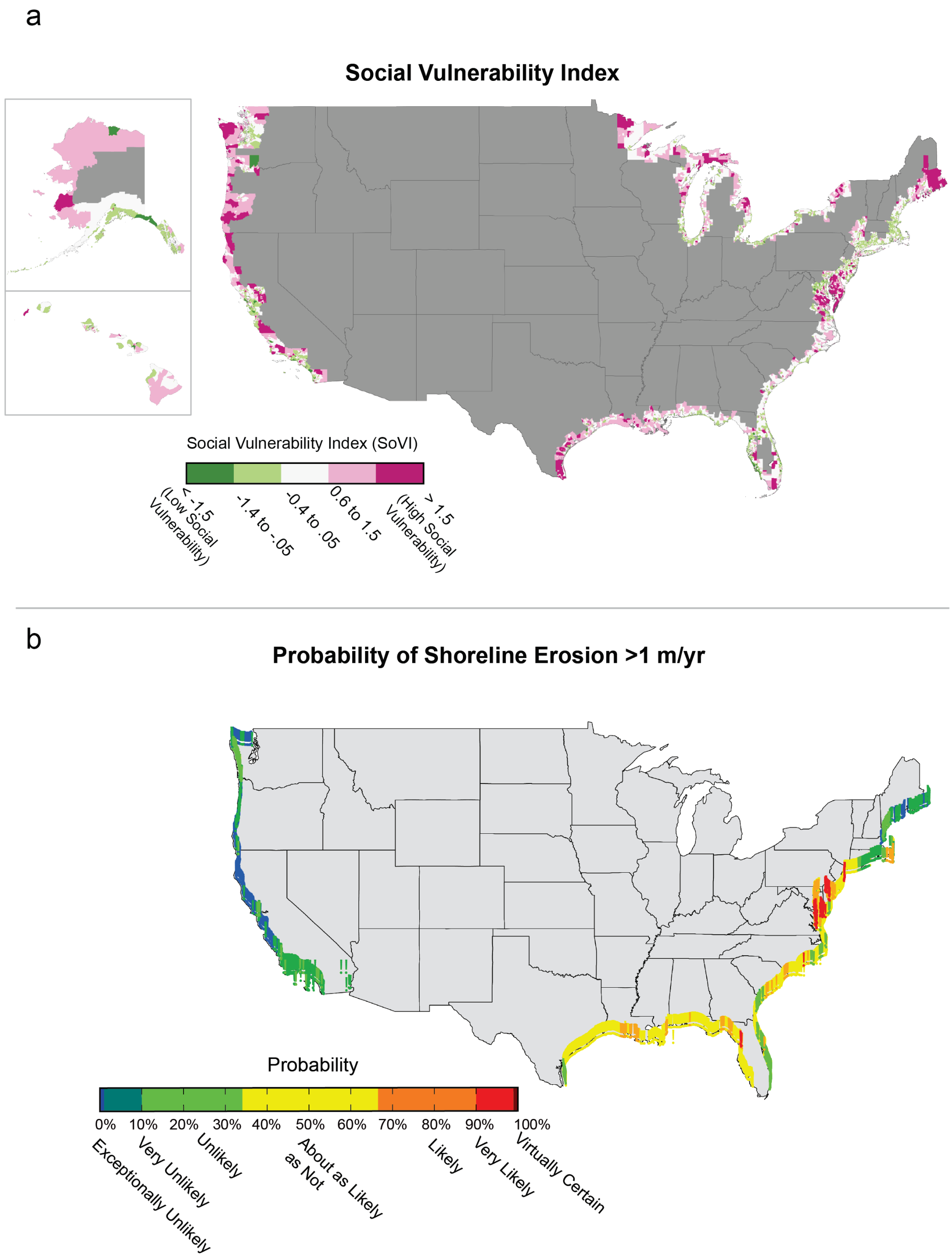
Figure 25.4: Social Vulnerability (a), Risk of Shoreline Change (b), Climate-Related Threats to U.S. Coastal Regions (c), and Adaptation Activities (d) (Four panels below will be integrated as overlays in a single figure in the final draft, and linked to a full set of references on adaptation examples and climate change threats.)

(a) Social Vulnerabilty Index (SoVI) at the Census tract level using procedures described in Martinich et al. (Martinich et al. 2012) and Schmidtlein et al. (Schmidtlein et al. 2008). Specific index components and weighting are unique to each region (North Atlantic, South Atlantic, Gulf, Pacific, and Great Lakes). All index components constructed from readily available Census data and include measures of poverty, age, family structure, rural vs. urban location, foreign-born status, wealth, gender, Native American status, and occupation.

(b) Risk of Shoreline Change (probability of a shoreline change >1m/yr) is based on methods described in Gutierrez et al. (Gutierrez 2011) with data as the basis for the mapped probabilistic information supplied by Thieler and Hammar-Klose (Thieler and Hammar-Klose 1999, 2000a; Thieler and Hammar-Klose 2000b).

(c) Regional Threats from Climate Change are compiled from technical input reports, the regional chapters in this report, and from the scientific literature (fully-referenced documentation will be provided in supplementary document).

(d) Examples of Adaptation Activities in Coastal Areas of the US and Affiliated Island States are compiled from technical input reports, the regional chapters in this report, the scientific literature, and other documentation available online (fully-referenced documentation will be provided in supplementary document).


a
Social Vulnerability Index
Social Vulnerability Index (SoVI)
< -1.5 (Low Social Vulnerability)
-1.4 to -.05
-0.4 to .05
0.6 to 1.5
> 1.5 (High Social Vulnerability)
b
Probability of Shoreline Erosion >1 m/yr
Probability
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Exceptionally Unlikely
Very Unlikely
Unlikely
About as Likely as Not
Likely
Very Likely
Virtually Certain


C
Regional Differences in Climate Change Threats
PACIFIC NORTHWEST
• Sea level rise is moderated by the continuing uplift of land, with few exceptions, such as the Seattle area.
• Commercial shellfish populations are suscepti-ble to shell thinning from ocean acidification.
• The region's relatively high economic dependence on commercial fisheries makes it sensitive to climate change impacts on marine species and ecosystem and related coastal ecosystems.
GREAT LAKES
• Higher temperatures and lengthened growing seasons in the Great Lakes region favor production of blue-green and toxic algae that can harm fish, water quality, habitat, and aesthetics.
• Increased winter air temperatures led to decreased Great Lakes ice cover, making shorelines more suseptible to erosion and flooding.
• Current projections of lake level changes are uncertain.
NORTHEAST
• Highly built-up coastal corridor concentrates population and supporting infrastructure.
• Storm surges from northeasters and hurricanes can cause significant damage.
• The historical rate of relative sea level rise varies across the region.
• Wetlands and estuaries are vulnerable to inundation from sea level rise; buildings and infrastructure are most vulnerable to higher storm suges as sea level rises.
CALIFORNIA
• Sea level has risen approximately 7 inches from 1900 to 2005, and is expected to rise at growing rates in this century.
• Higher temperatures, changes in precipitation, runoff and water supplies, and saltwater intrusion into coastal aquifers will result in negative impacts on coastal water resources.
• Coastal storm surges are expected to be higher due to increases in sea level alone, and more intense "atmospheric river systems" will increase coastal flooding risks from inland runoff.
• Expensive coastal development, critical infrastructure, and valuable coastal wetlands are at growing risk from coastal erosion, temporary flooding, and permanent inundation.
MID-ATLANTIC
• Rates of local sea level rise in the Chesapeake Bay are greater than globally averaged ones.
• Sea level rise threatens coastal homes, infrastructure and commercial develop-ment, including ports.
• Chesapeake Bay ecosystems are already heavily degraded, making them more vulnerable to climate-related impacts.
• Climate change and ocean acidification pose threats to Chesapeake Bay fisheries.
GULF COAST
• Hurricanes, land subsidence and sea level rise already pose great risks to Gulf Coast areas, placing homes, critical infrastructure, and people at risk, and causing permanent land loss.
• Coastal inland and water temperatures are expected to rise; and coastal inland areas are expected to become drier.
• There is still uncertainty about future frequency and intensity of Gulf of Mexico hurricanes but SLR will increase storm surges.
• The Florida Keys and coastal Louisiana are particularly vulnerable to additional sea-level rise.
HAWAII & PACIFIC ISLANDS
• Warmer and drier conditions will reduce freshwater supplies on many Pacific Islands, especially on low lying islands and atolls.
• Sea level rise will continue at accelerating rates, exacerbating coastal erosion, damaging infrastructure and agriculture, reducing critical habitat, and threatening shallow coral reef systems.
• Extreme water levels occur when high tides combine with interannual and interdecaldal sea level variations (e.g., ENSO, PDO, mesoscale eddy events) and storm surge.
• Coral reef changes pose threats to communities, cultures, and ecosystems.
ALASKA
• Summer sea ice is receding rapidly, altering marine ecosystems, allowing for greater ship access and offshore development, and making Native communities highly susceptible to coastal erosion.
• Ice loss from melting Alaskan and Canadian glaciers contributes almost as much to sea level rise currently as does melting of the Greenland Ice Sheet.
• Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries.
SOUTHEAST / CARIBBEAN
• A large number of cities, critical infrastructure, and water supplies are at low elevations and exposed to sea level rise.
• Ecosystems of the Southeast are vulnerable to loss from relative sea level rise, especially tidal marshes and swamps.
• Sea level rise will affect coastal agriculture through increasing the height of storm surge inundation, saltwater intrusion, and impacts on freshwater supplies.
• The number of land-falling tropical storms may decline, reducing important rainfall.
• The incidence of harmful algal blooms is expected to increase with climate change, as are health problems previously uncommon in the region.


d
Adaptation Examples
ALASKA
• Newtok, AK is relocating away from the eroding shoreline.
NORTHEAST
• Portland, ME is assessing costs for retrofitting its wastewater infrastructure.
• New Hampshire's Coastal Adaptation Workgroup is providing education, guidance, and networking for local planners.
• City of Boston considers adaptation and mitigation equal priorities, and sea level rise is a top concern.
• Connecticut State Assembly amended the state's Coastal Management Act to promote adaptation to sea level rise.
GREAT LAKES
• Wisconsin's state adaptation plan includes emphasis on lake shorefront areas.
• Bay-Lake Regional Planning Commission updated hazard mitigation plans.
• Ohio's Lake Erie Commission is in the process of developing model shoreline development legislation.
PACIFIC NORTHWEST
• Swinomish Tribe's Climate Change Initiative highlights special challenges of coastal tribes.
• Oregon Sea Grant surveyed its coastal professionals on preparedness for local climate change impacts.
MID-ATLANTIC
• Delaware launched a multi-faceted effort to prepare coastal communities for sea level rise
• Maryland's Comprehensive Strategy for Reducing Vulnerability to Climate Change has a strong initial focus on sea level rise and coastal hazards.
• Hampton Roads area and City of Norfolk, VA are working to reduce recurrent flooding and impacts on
CALIFORNIA
• San Diego Bay engaged in a multi-sector, multi-level stakeholder process to develop a first adaptation plan.
• California Ocean Protection Council developed sea level rise guidance to state and local governments.
• Bay Conservation & Development Commission passed Bay Plan Amendment.
GULF COAST
• Mississippi – Coastal Improvements Program includes buy-outs and relocation.
• 2012 Louisiana Coastal Master Plan ambitiously aims to protect and restore low-lying land.
• Entergy, America's Wetland Foundation, Oxfam champion joint adaptation planning for America's Energy Coast.
• Texas requires rolling easements.
SOUTHEAST / CARIBBEAN
• NC Department of Transportation is raising the road bed of US Highway 64 to account for future sea level rise.
• The City of Charleston upgraded stormwater pumps and sewer systems to reduce tidal flooding.
• Charlotte Harbor National Estuary Program and City of Punta Gorda, FL involved community stakeholders in its adaptation planning process.
• Southeast Florida Regional Climate Change Compact designated Adaptation Action Areas.
HAWAII & PACIFIC ISLANDS
• Researchers map sea level rise in Honolulu to help communities assess risks.
• USGS helps monitor saltwater intrusion on Majuro Atoll, Marshall Islands.

Coastal Lifelines at Risk

Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate changes.

Key coastal vulnerabilities arise from complex interactions among climate change and other physical, human, and ecological factors. These vulnerabilities have the potential to fundamentally alter life at the coast and disrupt coast-dependent economic activities.

Coastal infrastructure is exposed to climate change impacts from both the landward and ocean sides (Aerts and Botzen 2012; Bidwell et al. 2012; Biging et al. 2012; Bjerklie et al. 2012; Bloetscher et al. 2011; Burkett and Davidson 2012; DOT 2011; Flick and Murray 2003; Heberger et al. 2009; Irish et al. 2010; Kirshen et al. 2012; Markon et al. 2012; Marra et al. 2012; ORNL 2012; Poulter et al. 2009; Rosenzweig et al. 2011a; Weiss et al. 2011; Wilby and Keenan 2012). Some unique characteristics increase the vulnerability of coastal infrastructure to climate change (Ch. 11: Urban and Infrastructure) (Burkett and Davidson 2012; Zimmerman and Faris 2010). For instance, many coastal regions were settled long ago, making much of the infrastructure older than in other locations (ASCE 2012). Also, inflexibility of some coastal, water-dependent infrastructure, such as onshore gas and oil facilities, port facilities, thermal power plants, and some bridges, makes landward relocation difficult, while build-up of urban and industrial areas inland from the shoreline inhibit landward relocation (Burkett and Davidson 2012).

Infrastructure is built to certain site-specific design standards (such as the once-in-10-year, 24-hour rainstorm or the once-in-100-year flood) that take account of historical variability in climate, coastal, and hydrologic conditions. Impacts exceeding these standards can shorten the expected lifetime, incur greater maintenance costs, and decrease services. In general, higher sea levels, especially when combined with inland changes, will result in accelerated infrastructure impairment, with associated indirect effects on regional economies and a need for infrastructure upgrades, redesign, or relocation (Aerts and Botzen 2012; Bidwell et al. 2012; Biging et al. 2012; Bjerklie et al. 2012; Bloetscher et al. 2011; Burkett and Davidson 2012; DOT 2011; Flick and Murray 2003; Heberger et al. 2009; Irish et al. 2010; Kirshen et al. 2012; Marra et al. 2012; Poulter et al. 2009; Rosenzweig et al. 2011a; Weiss et al. 2011; Wilby and Keenan 2012).

Figure 25.5: Adaptation Possibilities for Coastal Infrastructure

Caption: This "mock-up" photo shows the existing Highway LA-1 and Leeville Bridge in coastal Louisiana (on the right) with a planned new, elevated bridge that would retain functionality under future, higher sea level conditions (center left). A 7-mile portion of the planned bridge has been completed and opened to traffic in December 2011. (Source: LA1-Coalition)

The more than 60,000 miles of coastal roads (Douglass et al. 2005) are essential for human activities in coastal areas (Ch. 5: Transportation), especially in case of evacuations during coastal emergencies (NOAA 2012e; U.S.A. Evacuation Routes 2012). Population growth to date and expected additional growth place growing demands on these roads, and climate change will decrease their functionality unless adaptation measures are taken (DOT 2012; Transportation Research Board 2011). Already, many coastal roads are affected during storm events (Federal Highway Administration 2008; Florida Department of Environmental Protection 2012; Texas General Land Office 2012; Wolshon 2006) and extreme high tides (California King Tides Initiative 2012; State of Washington 2012; Turner 2011; Watson 2011). Moreover, as coastal bridges, tunnels and roads are built or redesigned, engineers must account for inland and coastal changes, including drainage flooding, ground ice thaw, higher groundwater levels, and increasing saturation of roadway bases (Maine Department of Transportation 2003). During

Hurricane Katrina, many bridges failed because they had only been designed for river flooding but were also unexpectedly exposed to storm surges (Berry et al. 2012; DOT 2012).

Drainage and wastewater management systems constitute critical infrastructure for coastal businesses and residents (Ch. 3: Water Resources). With 20 of the 25 largest cities of the U.S. located along coastlines, saltwater intrusion in coastal aquifers will have widespread impacts (Solecki and Rosenzweig 2012). Wastewater treatment plants are typically located at low elevations to take advantage of gravity-fed sewage collection. Increased inland and coastal flooding make sewage treatment plants more vulnerable to disruption, while increased inflows will reduce treatment efficiency (County 2008; Daigger 2008; Daigger 2009; Flood and Cahoon 2011; Freas et al. 2010; Kirshen et al. 2011; Mailhot and Duchesne 2010; NYCDEP 2008; Rosenberg et al. 2010; Water Research Foundation 2012; WERF 2009). The drainage systems – designed using mid-20th century rainfall records – will drain less effectively in the future because of increased rainfall intensity (Changnon 2011; Peterson et al. 2012; Seneviratne et al. 2012; Ch. 2: Our Changing Climate) over more impervious surfaces (like asphalt and concrete) (Bierwagen et al. 2010; Bjerklie et al. 2012; Johnson 2012; Klein et al. 2003; Toll 2010), and reduced outlet capacity due to higher sea levels, resulting in more local flooding and combined sewer overflows (Center for Clean Air Policy and Environmental and Energy Study Institute 2012; EPA 2008). Together, these impacts on water systems increase the risks of urban flooding (Ch. 11: Urban and Infrastructure), deteriorating water quality, and human health impacts (Chillymanjaro 2011) (Ch. 9: Human Health). Wastewater system adaptations nationwide could cost utilities between $123 and $252 billion by 2050 (AMWA 2009).

The nation's energy infrastructure, such as power plants, oil and gas refineries, storage tanks, transformers, and electricity transmission lines, are often located directly in the coastal floodplain (Hayhoe et al. 2010; Perez 2009; Sathaye et al. 2011; Wilbanks et al. 2012). Roughly two-thirds of imported oil enters the U.S. through Gulf of Mexico ports (DOT 2012), where it is refined and then transported inland. Storm-related flooding and permanent inundation from sea level rise will disrupt these refineries (and related underground infrastructure) and, in turn, will constrain the supply of refined products to the rest of the nation unless adaptive measures are taken (Ch. 4: Energy Supply and Use; Ch. 10: Water, Energy, and Land Use; Francis et al. 2011; Rosato et al. 2008; Vugrin and Camphouse 2011; Vugrin et al. 2011; Zimmerman 2006).

Figure 25.6: Ecosystem Restoration

Caption: Coastal ecosystem restoration projects, such as the one shown in this example from New York City, help protect coastal waterfronts and maintain resilience of coastal infrastructure. Source: Department of City Planning, New York City, reprinted with permission.

To avoid these impacts, coastal infrastructure needs to be designed for changes in future inland and coastal conditions, including stressors not previously experienced in certain locations, as well as the possibility that infrastructure like bridges, roads, and culverts need more frequent replacing (Hallegatte 2008; U.S. Government 2009). Coastal communities have a variety of options to protect, replace, and redesign existing infrastructure, including flood proofing and flood protection through dikes, berms, pumps, elevation, or relocation. Relocation of large coastal infrastructure can be very expensive, however, and even the addition of new infrastructure in high-hazard zones is sometimes viewed as a more cost-effective option than siting elsewhere (SFRPC 2012; South Florida Regional Climate Change Compact 2012). A combination of built and natural infrastructure is increasingly recognized as a potentially cost-effective approach (Center for Clean Air Policy and Environmental and Energy Study Institute 2012; Davoudi et al. 2009; Jones et al. 2012; Nolon and Salkin 2011; Tzoulas et al. 2007) to reducing risks to communities and economies (Burkett and Davidson 2012; Irish and Resio 2010; Roseen et al. 2011).

BOX 25.1: Assessing Flood Exposure of Critical Facilities and Roads

NOAA's Critical Facilities Flood Exposure Tool provides an initial assessment of the risk to a community's critical facilities and roads within the "100-year" flood zone established by the Federal Emergency Management Agency (FEMA) (the 100-year flood zone is the aerial extent of a flood that has a 1% chance of occurring in any given year). The tool helps coastal managers quickly learn which facilities may be at risk – providing information that can be used to increase flood risk awareness and to inform a more detailed analysis and ultimately flood risk reduction measures. The critical facilities tool was initially created to assist Mississippi/Alabama Sea Grant in conducting its "Coastal Resiliency Index: A Community Self-Assessment" workshops and is now available for communities nationwide. For additional information contact: http://www.csc.noaa.gov/digitalcoast/tools/criticalfacilities

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Economic Disruption

Climate change increases exposure of nationally important assets, such as ports, tourism, and fishing sites, in coastal locations that are already vulnerable, threatening to disrupt economic activity beyond the coast and incurring significant costs for protecting or moving them.

Economic activity in coastal counties accounts for approximately 66 million jobs and $3.4 trillion in wages (NOAA 2011c) through a diversity of industries and commerce. In many instances, economic activity is fundamentally dependent on the physical and ecological characteristics of the coast. These features provide the template for coastal economic activities, including natural protection from waves, access to beaches, flat land for port development and container storage, and wetlands that support fisheries and provide flood protection.

More than 5,790 square miles (15,000 km^2) and more than $1 trillion of property and structures are at risk of inundation from sea level rise of two feet (66 cm) above current sea level – an elevation which could be reached by 2050 under a high rate of sea level rise of approximately 6.6 feet by 2100 (Parris et al. 2012), 20 years later assuming a lower rate of rise (4 feet by 2100) (Ch. 2: Our Changing Climate, Key Message 9), and sooner in areas of rapid land subsidence (Neumann et al. 2010a; Neumann et al. 2010b). Roughly half of the vulnerable property value is located in Florida, and the most vulnerable port cities are Miami, Greater New York, New Orleans, Tampa-St. Petersburg, and Virginia Beach (Biging et al. 2012; Cooley et al. 2012; Heberger et al. 2009; Neumann et al. 2010a).

Although comprehensive national estimates are not yet available, regional studies are indicative of the potential risk: the incremental annual damage of climate change to capital assets in the Gulf region alone could be $2.7 to $4.6 billion by 2030, and $8.3 to $13.2 billion by 2050; about 20% of these at-risk assets are in the oil and gas industry (America's Wetland Foundation et al. 2010). Investing approximately $50 billion for adaptation over the next 20 years could lead to approximately $135 billion in averted losses over the lifetime of adaptive measures (America's Wetland Foundation et al. 2010; State of Louisiana 2012).

More than $1.9 trillion in imports came through U.S. ports in 2010, with commercial ports directly supporting more than 13 million jobs (NOAA 2011) and providing 90% percent of consumer goods (Cordero 2011; IMO 2012; U.S. Navy 2007). Ports damaged during major coastal storms can be temporarily or permanently replaced by other modes of freight movement, but at greater cost (Ch. 5: Transportation). Although the stakes are high and adaptation options are available, a recent survey showed that most U.S. ports have not yet taken actions to adapt their operations to rising seas, increased flooding, and the potential for more extreme coastal storms (Becker et al. 2012).

Coast-to-Inland Economic Connection

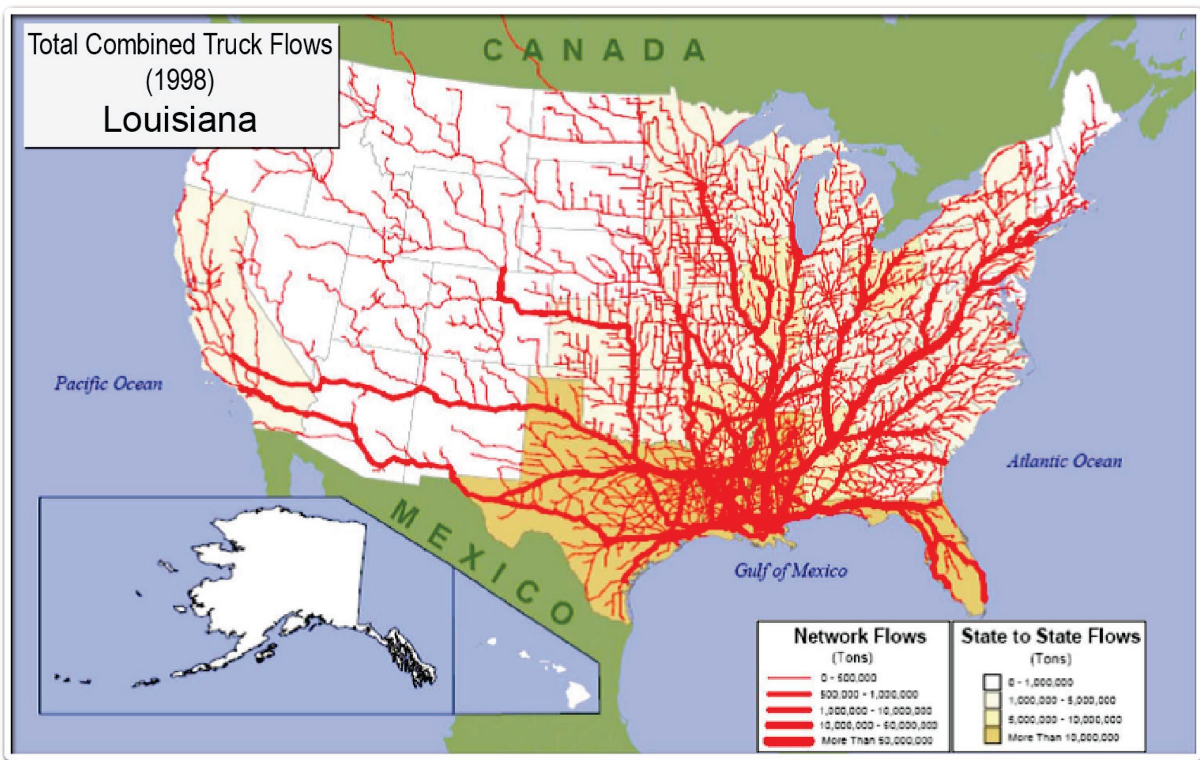

Figure 25.7: Coast-to-Inland Economic Connection

Caption: Coastal and inland economic activities are tightly linked. Such coast-hinterland connections can be temporarily disrupted from extreme events with significant economic implications for the rest of the nation. (Source: DOT) (Updated figure in preparation.)

Coastal recreation and tourism comprises the largest and fastest-growing sector of the U.S. service industry, accounting for 85% of the $700 billion annual tourism-related revenues (Houston 2008; NOAA 1998; U.S. Travel Association 2012), making this sector particularly vulnerable to increased impacts from climate change (NPCA 2012). Historically, development of immediate shoreline areas with hotels, vacation rentals, and other tourism-related establishments has frequently occurred without adequate regard for coastal hazards or shoreline dynamics (for example, inlet migration) (Nordstrom et al. 2011; Pendleton et al. 2012). Hard shoreline protection against the encroaching sea (like building sea walls or riprap) generally aggravates erosion and beach loss, and causes negative effects on coastal ecosystems, undermining the attractiveness of beach tourism. Thus "soft protection" through beach replenishment is increasingly preferred to "hard protection" measures. To continue the practice in the face of faster rising seas, sand replenishment would need to be undertaken more frequently, and thus at growing expense (Caldwell et al. 2012; Fletcher et al. 1997; Herrmann 1997; Kittinger and Ayers 2010; Leatherman and Gaunt 1989; Merrifield et al. 2012; NRC 1995, 2012; Pilkey and Dixon 1996).

U.S. oceanic and Great Lakes coasts are important centers for commercial and recreational fishing due to the high productivity of coastal ecosystems. In 2009, the U.S. seafood industry supported approximately 1 million full- and part-time jobs and generated $116 billion in sales and $32 billion in income (NMFS 2010). Recreational fishing also contributes to the economic engine of the coasts, with some 74 million saltwater fishing trips along U.S. coasts in 2009 generating $50 billion in sales and supporting over 327,000 jobs (NMFS 2010). Climate change threatens to disrupt fishing operations, through direct and indirect impacts to fish stocks (for example, temperature-related shifts in species ranges, changes in prey availability), as well as storm-related disruptions (Ch. 24: Ocean and Marine Resources).

Uneven Social Vulnerability

Socioeconomic disparities create uneven exposures and sensitivities to coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable from coastal areas.

In 2010, almost 24.6 million Americans lived within the 100-year floodplain or in neighborhoods that border the open ocean coast (Crossett et al. 2004; Crowell et al. 2010). Two trends will place even more people at risk in the future: the expansion of the floodplain as sea level rises, and the continuing immigration of people to coastal areas.

By 2100, the fraction of the U.S. population living in coastal counties is expected to increase by between 50% (46.2 million) under a scenario of substantial emissions reduction (B1) and 144% (131.2 million) under current emissions trends (EPA 2010; Nakicenovic et al. 2000). While specific population projections for future 100-year flood zones are only available for some locations (Carson and Montz 2009; Kleinosky et al. 2007), many of these new arrivals can be expected to locate in high-hazard areas. Thus, coastal population densities, along with increasing economic development, will continue to be an important factor in the overall exposure to climate change (Burkett and Davidson 2012; NOAA 2011b; Pielke Jr 2007; Strauss et al. 2012; Zhang and Leatherman 2011).

Despite persistent beliefs that living on the coast is reserved for the wealthy (Davis and Palumbo 2008; Neumann et al. 2010a; Zabel 2004), there are large social disparities in coastal areas that vary regionally (Burton and Cutter 2008; Cutter and Finch 2008; Emrich and Cutter 2011; Martinich et al. 2012; Moser and Ekstrom 2010a; Oxfam America 2009; Rygel et al. 2006). Full understanding of risk for coastal communities requires consideration of social vulnerability factors limiting people's ability to adapt. These factors include lower income, minority status, low educational achievement, advanced age, income dependencies, employment in low-paying service, retail, and other sectors, as well as being often place-bound, less economically and socially mobile, and much less likely to be insured than wealthy property owners (Bovbjerg 2007; Clark et al. 1998; Cutter et al. 2003; Moser et al. 2008; Texas Health Institute 2012) (see panel (a) in Figure 25.4).

For example, in California, an estimated 217,000 individuals are currently exposed to a 100-year flood; this number could double by 2100 as a result of a 4.6 foot sea level rise alone (roughly equivalent to the high end of the 1 to 4 foot range of sea level rise projections, Ch.2: Our Changing Climate) (Heberger et al. 2009). Approximately 18% of those exposed to high flood risk by the end of this century also fall into the "high social vulnerability" category (Cooley et al. 2012). This means that while many coastal property owners at the shorefront tend to be less socially vulnerable, adjacent populations just inland are often highly vulnerable.

Perhaps most important, adaptation options for highly socially vulnerable populations are limited (Cooley et al. 2012). Native communities in Alaska and Louisiana already face this challenge today (Textbox 25.2; Ch. 12, Tribal Lands and Resources)(Callaway et al. 1999; Louisiana Workshop 2012; Papiez 2009; Standen 2012; Tribal Climate Change Project 2008a, 2008b, 2010). Up to 50% of the areas with high social vulnerability face the prospect of unplanned retreat under the 1 to 4 foot range of projected sea level rise (Ch.2: Our Changing Climate), for several key reasons: they cannot afford expensive protection measures themselves, cost-benefit ratios don't favor public expense, or there is little support for a more orderly retreat process. By contrast, only 5% to 10% of the low social vulnerability areas are expected to face unplanned retreat (Martinich et al. 2012). This suggests that climate change could displace many socially vulnerable individuals and lead to significant social disruptions in some coastal areas (Titus et al. 2009).

BOX 25.2: Unique Challenges for Coastal Tribes

Coastal Native American and Native Alaskan populations, with their traditional dependencies upon natural resources, exhibit vulnerabilities that involve some unique challenges and capacities. Tribal adaptation options can be limited because tribal land boundaries are typically bordered by non-reservation lands, and climate change could force them to abandon traditionally important locations, certain cultural practices, and natural resources on which they depend. Tribes pride themselves for their experience and persistence in adapting to challenging situations. However, climate change presents a new challenge that is outside of the realm in which tribes have historically adapted (Ch. 12: Tribal Lands and Resources).

-- end box --

Vulnerable Ecosystems

Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.

Figure 25.8: Coastal Ecosystems Services

Caption: Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend for food, economic activities, inspiration, and enjoyment. This schematic illustrates many of these services situated in a Pacific or Caribbean island setting, but many of them can also be found along mainland coastlines.

Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend, including reducing the impacts from floods, buffering from storm surge and waves, and providing nursery habitat for important fish and other species, water filtration, carbon storage, and opportunities for recreation and enjoyment (Holzman 2012; Millennium Ecosystem Assessment 2005; Principe et al. 2012).

However, many of these ecosystems are rapidly being degraded by human impacts, including pollution, habitat destruction, and the spread of invasive species. For example, 75% of U.S. coral reefs in the Atlantic, Caribbean, and Gulf of Mexico are already in “poor” or “fair” condition (EPA 2012; Waddell and Clarke 2008); all Florida reefs are currently rated as “threatened” (Burke et al. 2011). Moreover, the incidence of low-oxygen “dead zones” in coastal waters has increased 30-fold in the U.S. since 1960, with over 300 coastal water bodies now experiencing stressful or lethal oxygen levels (Ch. 8, Ecosystems and Biodiversity) (CENR 2010). Coastal wetlands are being lost at high rates in Southeastern Louisiana (Couvillion et al. 2011; Diaz and Rosenberg 2008; Yuill et al. 2009).

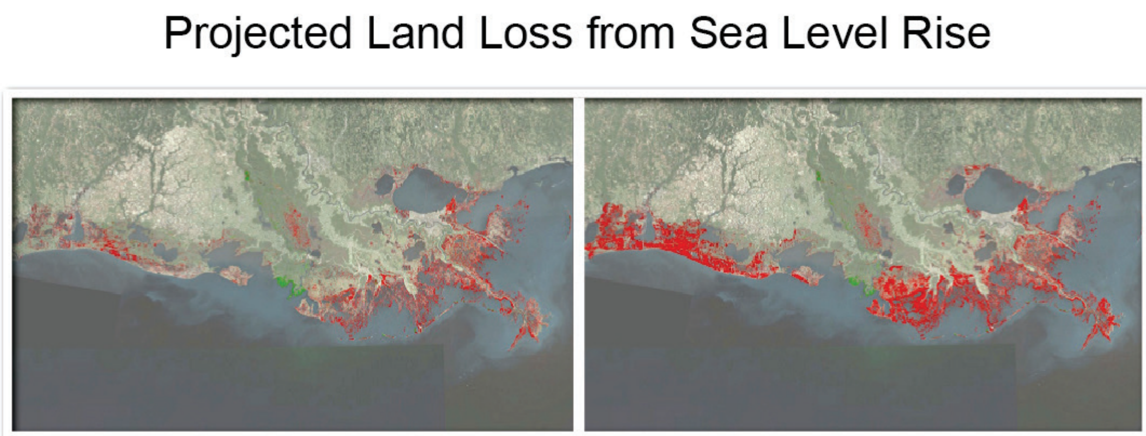

Figure 25.9: Projected Land Loss from Sea Level Rise

Caption: These maps show expected future land change in coastal Louisiana under two different scenarios of sea level rise. Land loss is influenced by factors other than sea level rise, including subsidence, river discharge and sediment load, and precipitation patterns. However, all these factors except sea level rise were held constant for this analysis. The panel on the right shows land change with a SLR of 10.6 inches between 2010 and 2060, while the one on the right assumes 31.5 inches of SLR rise for the same period. These amounts of SLR are within the projected SLR ranges for this time period (Ch. 2: Our Changing Climate). More information on the models that produced these maps can be found at www.coastalmasterplan.la.gov. (Source: State of Louisiana)

These existing stresses on coastal ecosystems will be exacerbated by effects of climate change, such as increased ocean temperatures that lead to coral bleaching (Hoegh-Guldberg et al. 2007), altered river flows affecting the health of estuaries (Petes et al. 2012), and acidified waters threatening shellfish (Barton et al. 2012). Climate change also affects the survival, reproduction, and health of coastal plants and animals in different ways. For example, changes in the timing of seasonal events (for example, breeding, migration), shifts in species distributions and ranges, changes in species interactions, and declines in biodiversity all combine to produce fundamental changes in ecosystem character, distribution, and functioning (Doney et al. 2012). Species with narrow physiological tolerance to change, low genetic diversity, specialized resource requirements, and poor competitive abilities are particularly vulnerable (Dawson et al. 2011; Feder 2010; Foden et al. 2008; Hoegh-Guldberg 1999; Hofmann and Todgham 2010; Montoya and Raffaelli 2010). Where the rate of climate change exceeds the pace at which plants and animals can acclimatize or adapt, impacts on coastal ecosystem will be profound (Alongi 2008; Craft et al. 2009; Kirwan et al. 2010). For example, high death rates of East Coast intertidal mussels at their southern range boundary have occurred because of rising temperatures between 1956 and 2007 (Jones et al. 2009). The presence of physical barriers, such as hardened shorelines, coastal development, and reduced sediment availability, and concurrent stressors such as pollution, habitat destruction, and invasive species will further exacerbate the ecological impacts of climate change and limit the ability of these ecosystems to adapt (Gedan et al. 2009; Glick et al. 2011; Williams and Grosholz 2008), as in the case of marshes attempting to migrate landward with sea level rise (Callaway et al. 2011; Craft et al. 2009; Feagin et al. 2010; Gedan et al. 2009; Kirwan et al. 2010; Phillips and Slattery 2006; Stralberg et al. 2011).

Of particular concern is the potential for coastal ecosystems to cross thresholds of rapid change ("tipping points"), beyond which they exist in an altered state or are lost entirely from the area; in some cases, these changes will be irreversible (Hoegh-Guldberg and Bruno 2010). These unique "no-analog" environments present serious challenges to resource managers, who are confronted with conditions never seen before (Barnosky et al. 2012; Burkett et al. 2005; CCSP 2009a; Nicholls et al. 2007). The ecosystems most susceptible to crossing such tipping points are those that have already lost some of their resilience due to degradation or depletion by non-climatic stressors (Folke et al. 2004). Certain coastal ecosystems are already rapidly changing as a result of interactions between climatic and non-climatic factors, and others have already crossed tipping points. Eelgrass in the Chesapeake Bay died out almost completely during the record-hot summer of 2005, when temperatures exceeded the species' tolerance threshold of 86°F (30°C) (Moore and Jarvis 2008), and subsequent recovery has been poor (Jarvis and Moore 2010). Severe low-oxygen events have emerged as a novel phenomenon in the Pacific Northwest due to changes in the timing and duration of coastal upwelling (Barth et al. 2007; Chan et al. 2008). These have led to high mortality of Dungeness crabs (Grantham et al. 2004) and the temporary disappearance of rockfish (Chan et al. 2008), with consequences for local fisheries. Reducing non-climatic stressors at the local scale can potentially prevent crossing some of these tipping points (Biggs et al. 2009; Hsieh et al. 2008; Kelly et al. 2011; Lubchenco and Petes 2010; Sumaila et al. 2011).

Adaptation Planning

Growing awareness of the high vulnerability of coasts to climate change increasingly leads coastal regions to plan for potential impacts on their citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.

Considerable progress has been made since 2009 in both coastal adaptation science and practice (Figure 25.4, panel (d)), though significant gaps in understanding, planning, and implementation remain (Blakely and Carbonell 2012; Brugmann 2011, 2012; Gregg et al. 2011; Hart et al. 2012; Moser and Ekstrom 2012; NRC 2010). U.S. coastal managers pay increasing attention to adaptation, but are mostly still at an early stage of building their capacities for adaptation rather than implementing structural or policy changes (Ch. 28: Adaptation; Hart et al. 2012; Moser 2009; NRC 2010). Although well familiar with historical approaches to structural shoreline protection, managers are less familiar with some of the more innovative approaches to coastal adaptation, such as rolling easements (Titus et al. 2009), ecosystem-based adaptation, or managed retreat (Grannis 2011; Hart et al. 2012). There is only limited evidence of more substantial ("transformational") adaptation occurring (Ch. 22: Alaska and Arctic; Kates et al. 2012; Marino 2012; State of Louisiana 2012).

Coastal populations show growing concern about climate related impacts and support the development of adaptation plans (Borberg et al. 2009; Goidel et al. 2012; Hart et al. 2012; Leiserowitz et al. 2011a, 2011b; Responsive Management 2010; The Mellman Group 2011), but support for development restrictions or managed retreat is limited (Agyeman et al. 2009; Fresque-Baxter and Armitage 2012; Goidel et al. 2012; Hart et al. 2012; Kick et al. 2011; Leiserowitz et al. 2011b; Responsive Management 2010; Wetlands Watch Inc 2012; Yale Climate Media Forum 2012). Economic interests and population trends tend to favor continued (re)development and in-fill in near-shore locations. Current disaster recovery practices frequently promote rapid rebuilding on site with limited consideration for future conditions (Kyler 2012; Schrope 2010) despite clear evidence that more appropriate siting and construction can substantially reduce future losses (Multihazard Mitigation Council 2005; U.S. Army Corps of Engineers 2012).

Enacting measures that increase resilience in the face of current hazards while reducing long-term risks due to climate change continues to be challenging (Hudson 2012; IPCC 2012), especially in light of the fact that most of the National Flood Insurance Program's repetitive flood losses occur in coastal counties (GAO 2004; King 2005). A robust finding is that the cost of preventive hazard mitigation is 4 to 10 times lower than the cost of inaction (Multihazard Mitigation Council 2005; Neumann et al. 2010a). Even so, prioritizing expenditures now whose benefits accrue far in the future is difficult (Cropper and Portney 1990). Moreover, cumulative costs to the economy of responding to sea level rise and flooding events alone could be as high as $325 billion by 2100 for 4 feet of sea level rise, with $130 billion expected to be incurred in Florida and $88 billion in the North Atlantic region (Neumann et al. 2010b). The projected costs associated with one foot of sea level rise by 2100 are roughly $200 billion, not including indirect losses from business disruption, lost economic activity, impacts on economic growth, or the non-market losses (Franck 2009; Hallegatte 2012; Heinz Center 2000a; Neumann et al. 2010b). Such indirect losses, even in regions generally well-prepared for disaster events, can be substantial (in the tens of billions of dollars) as Superstorm Sandy, followed by nor'easter Athena, in fall 2012 illustrated. Sequences of extreme events that occur over a short period not only reduce the time available for natural and social systems to recover and for adaptation measures to be implemented, but also increase the cumulative effect of back-to-back extremes compared to the same events occurring over a longer period (Greening et al. 2006; IPCC SREX 2012; Miao et al. 2009; Paerl et al. 2001; Peterson et al. 2008). The cost of managed retreat requires further assessment.

Property insurance can serve as an important mode of financial adaptation to climate risks (Barthel and Neumayer 2010), but the full potential of insurance has not yet been realized (Burkett and Davidson 2012; GAO 2010; Ntelekos et al. 2010). At present, the second greatest physical liability of the U.S. government behind Social Security is the National Flood Insurance Program. While insured assets in coastal areas represent only a portion of this total liability, taxpayers are currently (as of 2010) responsible for $510 billion of insured assets in the coastal Special Flood Hazard Area (SFHA) (Mills et al. 2005; NOAA 2012e; Thomas and Leichenko 2011). However, a number of reforms in the National Flood Insurance Program have been identified and enacted in 2012 to ensure that the program is fiscally sound and hazard mitigation is improved (Czajkowski et al. 2011; Heinz Center 2000b; Kunreuther and Michel-Kerjan 2009; Michel-Kerjan and Kunreuther 2011; Michel-Kerjan 2010).

Climate adaptation efforts that integrate hazard mitigation, natural resource conservation, and restoration of coastal ecosystems can enhance ecological resilience and reduce the exposure of property, infrastructure, and economic activities to climate change impacts (Figure 25.6) (Colls et al. 2009; Danielsen et al. 2005; Principe et al. 2012; Swann 2008; The World Bank 2009; Tobey et al. 2010; UNEP et al. 2006; Villanoy et al. 2012). Yet, the integration and translation of scientific understanding of the benefits provided by ecosystems into engineering design and hazard management remains challenging (Daily et al. 2009; Koch et al. 2009). Moreover, interdependencies among functioning infrastructure types and coastal uses require an integrated approach across levels of government, but fragmented governance at the managerial, financial, and regulatory levels, and narrow professional training, job descriptions, and agency missions pose significant barriers (Ch. 11: Urban and Infrastructure; Amundsen et al. 2010; Burch 2010; McNeeley 2012; Measham et al. 2011; Moser and Ekstrom 2010, 2012; Hanemann et al. 2012). Adaptation efforts to date that have begun to connect across jurisdictional and departmental boundaries and create innovative solutions are thus extremely encouraging (Burkett and Davidson 2012; Georgetown Climate Center 2012; Moser and Ekstrom 2012; NPCC 2009; NYAS 2012).

Traceable Accounts

Chapter 25: Coastal Zone, Development and Ecosystems

Key Message Process: A central component of the assessment process was a Chapter Lead Authors meeting held in St. Louis, Missouri in April 2012. The key messages were initially developed at this meeting. Key vulnerabilities were operationally defined as those challenges that can fundamentally undermine the functioning of human and natural coastal systems. They arise when these systems are highly exposed and sensitive to climate change and (given present or potential future adaptive capacities) insufficiently prepared or able to respond. The vulnerabilities that the team decided to focus on were informed by ongoing interactions of the author team with coastal managers, planners, and stakeholders as well as a review of the existing literature. In addition, the author team conducted a thorough review of the technical inputs and associated literature, including the coastal zone foundational document prepared for the NCA (Burkett and Davidson 2012). Chapter development was supported by numerous chapter author technical discussions via teleconference from April to June 2012.

Key message #1/5	**Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate-related changes.**
Description of evidence base	Coastal infrastructure is defined here to include: buildings, roads, railroads, airports, port facilities, subways, tunnels, bridges, water supply systems, wells, sewer lines, pump stations, wastewater treatment plants, water storage and drainage systems, port facilities, energy production and transmission facilities on land and offshore, flood protection systems such as levees and seawalls, and telecommunication equipment. Lifelines are understood in the common usage of that term in hazards management. The key message and supporting text summarizes extensive evidence documented in the coastal zone Technical Input (Burkett and Davidson 2012) and well as in Wilbanks et al. (2012). Technical Input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant scientific literature. Additional evidence is provided in (Burkett and Davidson 2012), Chapter 2: Climate Science, Chapter key message #8 about hurricanes, and #9 regarding global sea level. For key coastal transportation vulnerabilities see Chapter 5, Transportation. For more discussion of energy-related infrastructure see Chapter 4, Energy Supply and Use. This section focuses mainly on water supply and energy infrastructure and evacuation routes, as they constitute critical lifelines. The evidence base for exposure, sensitivity and adaptive capacity to higher sea levels and storm surges is very strong, both from empirical observation/ historical experience and studies projecting future impacts on critical coastal infrastructure. There are numerous publications concerning the effects of sea level rise and storm surges on roadways, coastal bridges, and supply of refined products. The information on roadways came from various reports (for example, Transportation Research Board (Transportation Research Board 2011); U.S. Department of Transportation (DOT 2012) and publications (for example, (State of Louisiana 2012). The impact on coastal bridges is documented in DOT reports (DOT 2012; Maine Department of Transportation 2003). A number of publications explored the impacts on supply of refined products (Francis et al. 2011; Rosato et al. 2008; Vugrin and Camphouse 2011; Vugrin et al. 2011; Zimmerman 2006). The evidence base is moderate for the interaction of inland and coastal flooding. There are many publications concerning impacts to wastewater treatment plants and drainage systems. With some of the most recent ones concerning wastewater

	treatment plants being (Flood and Cahoon 2011; Kirshen et al. 2011), and a (Water Research Foundation 2012). The most recent publications concerning drainage systems include Peterson et al. (2012), Seneviratne et al. (2012), Bjerklie et al. (2012), and Johnson (2012). These lead to increased risk of urban flooding.
New information and remaining uncertainties	The projected rate of Sea Level Rise (SLR): Fully accounted for through the use of common scenarios (we note, however, that there is currently limited impacts literature yet that uses the lowest or highest 2100 scenario and none that specifically use the broader range of IPCC SLR and NCA land use scenarios.) The severity and frequency of storm damage in any given location cannot yet be fully accounted for due to uncertainties in projecting future extratropical and tropical storm frequency, intensity, and changes in storm tracks for different regions (Burkett and Davidson 2012; Ch. 2: Our Changing Climate). The timely implementation and efficacy of adaptation measures, including planned retreat, in mitigating damages is accounted for in the underlying literature (for example, by varying assumptions about the timing of implementation of adaptation measures and the type of adaptation measures). However, such studies can only test the sensitivity of conclusions to these assumptions; they do not allow statements about what is occurring on the ground. Additional uncertainties arise from the confluence of climate change impacts from the inland and ocean side, which have yet to be studied in an integrated fashion across different coastal regions of the U.S.
Assessment of confidence based on evidence	**Coastal lifelines, such as water infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate-related changes.** Given the evidence base, the large quantity of infrastructure in the coastal zone, and the directional trend at least of sea level rise and runoff associated with heavy precipitation events, we have **very high** confidence that infrastructure in the coastal zone resources is increasingly vulnerable.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 25: Coastal Zone, Development and Ecosystems

Key Message Process: See key message #1.

Key message #2/5	**Climate change increases exposure of nationally important assets, such as ports, tourism and fishing sites, in already-vulnerable coastal locations, threatening to disrupt economic activity beyond the coast and incurring significant costs for protecting or moving them.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the coastal zone Technical Input (Burkett and Davidson 2012). Technical Input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, as well as the extant scientific literature. The evidence base for increased exposure to assets is strong. Many publications have assessed at risk areas (e.g., Biging et al. 2012; Cooley et al. 2012; Heberger et al. 2009; Neumann et al. 2010a). Highly reliable economic activity information is available from recurring surveys conducted by NOAA and others, and asset exposure is conclusively demonstrated by historical information (from storm and erosion damage), GIS-based location and LIDAR and other forms of elevation data, and numerous vulnerability and adaptation studies of the built environment (see also technical input reports on urban/infrastructure (Wilbanks et al. 2012) and transportation (DOT 2012), as well as Ch. 11: Urban and Infrastructure, Ch. 4: Energy Supply and Use, and Ch. 5: Transportation. A number of studies, using various economic assumptions, exist that aim to assess the cost of protecting or relocating coastal assets and services. Many publications and reports explore the cost of replacing services offered by ports (Caldwell et al. 2012; DOT 2012) though (Becker et al. 2012) notes that few ports are implementing adaptation practices to date. The economic consequences of climate change on tourism is supported by a number of studies (most recent being: (Caldwell et al. 2012; Merrifield et al. 2012; Nordstrom et al. 2011; NPCA 2012; Pendleton et al. 2012). The threats of climate change on fishing have been explored in (Burkett and Davidson 2012). Additional evidence comes from empirical observation: public statements by private sector representatives and public officials indicate high awareness of economic asset exposure and a determination to see those assets protected against an encroaching sea, even at high cost (New York City, Miami Dade Co., San Francisco airport etc.). The economic value of exposed assets and activities is frequently invoked when they get damaged or interrupted during storm events (e.g., Hallegatte 2012). Threats to economic activity are also consistently cited as important to local decision-making in the coastal context (e.g., Titus et al. 2009).
New information and remaining uncertainties	The projected rate of sea level rise: Fully accounted for through the use of common scenarios (we note, however, that there is currently limited impacts literature yet that uses the lowest or highest 2100 scenario and none that specifically use the broader range of IPCC SLR and NCA land use scenarios.) The projected severity and frequency of storm damage in any given location cannot yet be fully accounted for due to uncertainties in projecting future extratropical and tropical storm frequency, intensity, and changes in storm tracks for different regions (Burkett and Davidson 2012). The timely implementation and efficacy of adaptation measures, including planned retreat, in mitigating damages:

	Accounted for in the underlying literature (for example, by varying assumptions about the timing of implementation of adaptation measures, the type of adaptation measures, and other economic assumptions such as discount rates). However, such studies can only test the sensitivity of conclusions to these assumptions; they do not allow statements about what is occurring on the ground. Well established post-hoc assessments by the Multihazard Mitigation Council (Multihazard Mitigation Council 2005) suggest that hazard mitigation action is highly cost-effective (for every dollar spent, $4 dollars in damages are avoided), yet current work finds that mitigation actions are rarely adopted by coastal property owners, thus current assessments of the cost of rational adaptation may underestimate the real cost.
Assessment of confidence based on evidence	Given the evidence base, the well-established accumulation of economic assets and activities in coastal areas, and the directional trend of sea level rise, we have **very high** confidence in the main conclusion that resources and assets that are nationally important to economic productivity are threatened by SLR and climate change. While there is currently no indication that the highest-value assets and economic activities are being abandoned in the face of sea level rise and storm impacts, we have **very high** confidence that the cost of protecting these assets in place will be high, and higher the faster (relative) sea level rises. We have **very high** confidence that adequate planning and arrangement for future financing mechanisms, timely implementation of hazard mitigation measures and effective disaster response will keep the economic impacts and adaptation costs lower than if these actions are not taken. Due to uncertainties in asset-specific elevation above SL, the presence and efficacy of protective measures – at present and in the future, the feasibility of relocation in any one case, and uncertainties in future storm surge heights and storm frequencies, we are not able to assess timing or total cost of protecting or relocating economic assets with any confidence at this time.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 25: Coastal Zone, Development and Ecosystems

Key Message Process: See key message #1.

Key message #3/5	**Socioeconomic disparities create uneven exposures and sensitivities to coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable from coastal areas.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the coastal zone Technical Input (Burkett and Davidson 2012). Technical Input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature. Moderate: Assessment of the social vulnerability to coastal impacts of climate change is a comparatively new research focus in the US; clearly an advance since the 2009 NCA. There are currently multiple published, peer-reviewed studies, by different author teams, using different vulnerability metrics, which all reach the same conclusion: economically and socially vulnerable individuals and communities face significant coastal risks and have a lower adaptive capacity than less socially vulnerable populations. Studies have shown that the US coastal population is growing (EPA 2010; Nakicenovic et al. 2000) and have assessed their importance for climate change exposure (Pielke Jr 2007; Strauss et al. 2012; Zhang and Leatherman 2011). There are numerous publications on the social factors that play key roles in coastal vulnerability (Bovbjerg 2007; Clark et al. 1998; Cooley et al. 2012; Cutter et al. 2003; Moser et al. 2008; Texas Health Institute 2012) There is an additional body of evidence emerging in the literature that also supports this conclusion, namely the growing literature on “barriers to adaptation”, particular from studies conducted here in the U.S. (Burkett and Davidson 2012; Callaway et al. 2011; Cooley et al. 2012; Moser and Ekstrom 2012; Papiez 2009; Standen 2012; Tribal Climate Change Project 2010). This literature reports on the limitations poorer communities face at present in beginning adaptation planning, and on the challenges virtually all communities face, in prioritizing adaptation and moving from planning to implementation of adaptation options. There is empirical evidence for how difficult it is for small, less wealthy communities (for example, the Native communities in Alaska or on some of Louisiana’s barriers islands) to obtain federal funds to relocate from eroding shorelines (various technical input reports). Eligibility criteria (positive benefit-cost ratios) make it particularly difficult for low-income communities to obtain such funds; current federal budget constraints limit the available resources to support managed retreat and relocation (GAO 2004, 2010). The recent economic hardship has placed constraints even on the richer coastal communities in the US in developing and implementing adaptation strategies (for example, in California; (Moser and Ekstrom 2012). While the economic situation, funding priorities, or institutional mechanisms to provide support to socially vulnerable communities will not remain static over time, there is no reliable scientific evidence for how these factors may change in the future.
New information and remaining uncertainties	The body of research on this topic is largely new since 2009. Each of the peer-reviewed studies discusses data gaps and methodological limitations, as well as the particular challenge of projecting demographic variables – a notoriously difficult undertaking – forward in time. The conclusion is limited by uneven coverage of in-depth vulnerability studies; although those that do exist are consistent with and confirm the conclusions of the national study completed by (Martinich et al. 2012).

	The latter study was extended by applying the same approach, data sources, and methodology to regions previously not yet covered, thus closing important informational gaps (Hawaii, Alaska, the Great Lakes region). Data gaps remain for most coastal locations in the Pacific islands, Puerto Rico, and other U.S. territories. The most important limit on understanding is the current inability to project social vulnerability forward in time. While some social variables are more easily predicted (for example, age and gender distribution) than others (for example, income distribution, ethnic composition and linguistic abilities), the predictive capability declines the further out projections aim (beyond 2030 or 2050), and it is particularly difficult to project these variables in specific places subject to coastal risks, as populations are mobile over time, and no existing model reliably predicts place-based demographics at the scale important to these analyses.
Assessment of confidence based on evidence	We have **high** confidence in this conclusion, as it is based on well-accepted techniques, replicated in several place-based case studies, and a nationwide analysis, using reliable Census data. Consistency in insights and conclusions in these studies, and in others across regions, sectors, and nations, add to the confidence. The conclusion does involve significant projection uncertainties, however, concerning where socially vulnerable populations will be located in several decades from now. Sensitivity analysis of this factor, and overall a wider research base is needed before a higher confidence assessment can be assigned.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #4/5	**Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the coastal zone Technical Input (Burkett and Davidson 2012). Technical Input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature. Strong: "Coastal ecosystems are particularly vulnerable to climate change because they have already been dramatically altered by human stresses" The degradation and depletion of coastal systems due to human stresses (for example, pollution, habitat destruction, overharvesting) has been widely documented throughout the U.S. and the world (Burke et al. 2011; CENR 2010; Couvillion et al. 2011; Diaz and Rosenberg 2008; EPA 2012; Waddell and Clarke 2008; Yuill et al. 2009). The degree of degradation varies based on location and level of human impact. However, evidence of degradation is available for all types of U.S. coastal ecosystems, from coral reefs, to seagrasses and rocky shores. Human stresses can be direct (for example, habitat destruction due to dredging of bays) or indirect (for example, food web disruption due to overfishing). There is also consistent evidence that ecosystems degraded by human activities are less resilient to changes in climatic factors, such as water temperature, precipitation, and sea level rise. Strong: "climate change will result in further reduction or loss of the services that these ecosystems provide," The impacts of changing coastal conditions (for example, changes associated with altered river inflows, higher temperatures, and the effects of high rates of relative sea level rise) on coastal ecosystems and their associated services have been extensively documented through observational and empirical studies (Some recent publications: (Barton et al. 2012; Dawson et al. 2011; Doney et al. 2012; Glick et al. 2011; Petes et al. 2012; Stralberg et al. 2011). Many models of coastal ecosystem responses to climatic factors have been well-validated with field data. Given the existing knowledge of ecosystem responses, future climate projections, and the interactions with non-climatic stressors that further exacerbate climatic impacts, evidence of the potential for further reduction and/or loss is strong. Suggestive: "including potentially irreversible impacts." Severe impacts (for example, mass coral bleaching events, rapid species invasions) have been extensively documented for U.S. coastal ecosystems. Many experts have suggested that some of these impacts may be irreversible (Hoegh-Guldberg and Bruno 2010) and never before seen conditions are documented (Burkett et al. 2005; CCSP 2009a; Nicholls et al. 2007). Recovery may or may not be possible in different instances; this depends on factors that are not well-understood, such as the adaptive capacity of ecosystems, future projections of change that consider interactions among multiple climatic and non-climatic human alterations of systems, the dynamics and persistence of alternative states that are created after a regime shift has occurred, and whether or not the climatic and/or non-climatic

	stressors that lead to impacts will be ameliorated (Barth et al. 2007; Chan et al. 2008; Folke et al. 2004; Grantham et al. 2004; Jarvis and Moore 2010; Moore and Jarvis 2008).
New information and remaining uncertainties	Since 2009, new studies have added weight to previously already established conclusions. The major advance lies in the examination of tipping points for species and entire ecosystems. Existing uncertainties and future research needs were identified through reviewing the NCA technical inputs and other peer-reviewed, published literature on these topics, as well as through our own identification and assessment of knowledge gaps. Key uncertainties in our understanding of ecosystem impacts of climate change in coastal areas are associated with: • the interactive effects and relative contributions of multiple climatic and non-climatic stressors on coastal organisms and ecosystems; • how the consequences of multiple stressors for individual species combine to affect community- and ecosystem-level interactions and functions; • projected magnitude of coastal ecosystem change under different scenarios of temperature change, sea level rise, and land-use change, particularly given the potential for feedbacks and non-linearities in ecosystem response; • the potential adaptive capacity of coastal organisms and ecosystems to climate change; • trajectories, timeframes, and magnitudes of coastal ecosystem recovery; • the dynamics and persistence of alternative states that are created after ecosystem regime shifts have occurred; and • the potential and likelihood for irreversible climate-related coastal ecosystem change. In general, relatively little work to date has been conducted to project future coastal ecosystem change under integrative scenarios of temperature change, sea level rise, and changes in human uses of, and impacts to, coastal ecosystems (for example, through land-use change). Advancing understanding and knowledge associated with this key uncertainty, as well as the others included in the above list, would be fostered by addressing the research needs described below.
Assessment of confidence based on evidence	We have **very high** confidence that coastal ecosystems are particularly vulnerable to climate change because they have already been dramatically altered by human stresses as documented in extensive and conclusive evidence. We have **very high** confidence that climate change will result in further reduction or loss of the services that these ecosystems provide, as there is extensive and conclusive evidence related to this vulnerability. We have **high** confidence that climatic change will include “potentially irreversible impacts." Site-specific evidence of potentially irreversible impacts exists in the literature. This vulnerability is frequently identified by studies of coastal ecosystems. However, methods, research, and models for understanding, documenting, and predicting potentially irreversible impacts across all types of coastal ecosystems are still being developed.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #5/5	**Growing awareness of the high vulnerability of coasts to climate change increasingly leads coastal regions to plan for potential impacts on their citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the coastal zone Technical Input (Burkett and Davidson 2012). Technical Input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature. Moderate to strong: The results on which this conclusion relies are based on case studies, direct observation and "lessons learned" assessments from a wide range of efforts, surveys, and interview studies in ongoing adaptation efforts around the country. There has been some planning for remediating climate change impacts (Some recent publications include: (Goidel et al. 2012; Hart et al. 2012; Hudson 2012; IPCC 2012)) and there are publications on the many barriers that affect adaptation (Amundsen et al. 2010; Burch 2010; McNeeley 2012; Measham et al. 2011; Moser and Ekstrom 2010a; Moser and Ekstrom 2012) (Hanemann, 2012;). In addition there is confirming evidence of very similar findings from other locations outside the US (some, from Canada, were also submitted as Technical Input Reports to the NCA), such as the UK, continental Europe, Australia, and others (Agyeman et al. 2009; Amundsen et al. 2010; Burch 2010; Fresque-Baxter and Armitage 2012; Measham et al. 2011) .
New information and remaining uncertainties	Adaptation is a rapidly spreading policy and planning focus across coastal America. This was not previously captured in the 2009 NCA and is thus a major advance in understanding, including what adaptation activities are underway, what impedes them, and how coastal stakeholders view and respond to these activities. Given the local nature of adaptation (even though it frequently involves actors from all levels of government), it is difficult to systematically track, catalog, or assess progress being made on adaptation in coastal America. The difficulty, if not impossibility, of comprehensively tracking such progress has been previously acknowledged in (NRC 2010). This conclusion is reiterated in the Adaptation Chapter of this report. While the findings and integrative conclusion stand on strong evidence, some uncertainties about US coastal regions' adaptive capacity, the level of adoption of hazard mitigation and other adaptation strategies, the extent and importance of barriers to adaptation remain. Possibly the least well understood aspect about coastal adaptation is how and when to undertake large-scale, transformational adaptation.
Assessment of confidence based on evidence	We have **very high** confidence in this conclusion, as it is primarily based on studies using well-accepted social science research techniques (for example, surveys, interviews, participant observation), replicated in several place-based case studies, and a nationwide compilation of adaptation case studies. Consistency in insights and conclusions in these studies, and in others across regions, sectors, and nations, add to the confidence.

	As described above, a comprehensive catalogue of all adaptation efforts, and of related challenges and lessons learned, is difficult if not impossible to ever obtain. Nevertheless, the emerging insights and evidence from different regions of the country provides considerable confidence that the situation is reasonably well captured in the documents relied on here. The coastal stakeholders represented on the Burkett and Davidson, 2012, Chapter team confirmed the conclusions from their long-term experience in coastal management and direct involvement in adaptation efforts locally. Moreover, evidence from other regions outside the U.S. add weight to the conclusions drawn here.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Introduction to Response Strategies

Citizens of the United States and the world make choices every day that change the risks of current and future climate change. The impacts of climate change are already evident, and have been directly and unequivocally linked to human activities. To the extent that we can anticipate future changes, society can make better decisions about how to reduce risk and protect people, places, and ecosystems from extreme events and long-term changes. Some but not all of these changes are inevitable. Clearly, decisions made now and in the future will influence society's resilience to natural, social, and economic impacts of future climate change.

In recognition of the significance of these decisions, the 2013 National Climate Assessment Report presents information that is useful for a wide variety of decisions within regions and sectors, at multiple scales, and over multiple time frames. For the first time, this Assessment includes chapters on Adaptation, Mitigation, and Decision Support, in addition to identifying research needs associated with these topics. Further, this report includes a chapter on the Sustained Assessment Process, which describes the rationale for ongoing assessment activity to achieve greater efficiency and better scientific and societal outcomes.

As with other sections of this report, the linkages across the chapters are extremely important. There are direct connections between mitigation decisions (about whether and how to manage emissions of heat-trapping gases) and how much climate will change in the future. The amount of change that occurs will in turn dictate the amount of adaptation that will be required. The Adaptation chapter assesses current adaptation activities across the U.S. in the public and private sectors, and concludes that although a lot of adaptation planning is being done, implementation of adaptation plans lags significantly behind the scale of anticipated changes. The Mitigation chapter describes emissions trajectories and assesses the state of mitigation activities – which are increasing but are still not keeping pace with global goals to manage emissions. In the Decision Support chapter, a variety of approaches to bridge the gap between scientific understanding and decision-making are discussed, leading to the conclusion that there are many opportunities to help scientists understand the needs of decision-makers, and also to help decision-makers use available tools and information to reduce the risks of climate change.

26. Decision Support
Supporting Policy, Planning, and Resource Management Decisions in a Climate Change Context

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Key Messages

1. **Creating well-structured, transparent, and collaborative decision processes involving researchers and stakeholders is as important to effective decision-making as having good scientific information and tools. An effective process will better enable decision-makers to apply complex information to decisions, consider uncertainties associated with climate variability and change, assess the wide range of possible human responses, and engage institutions and individuals who are potentially affected.**
2. **Many decision frameworks and tools are available to support and improve decision-making on climate change adaptation and ways to reduce future climate change.**
3. **Steps to improve collaborative decision processes could include training more “science translators” to help bridge science and decision-making; integrating development of decision support tools into fundamental scientific research; improving reward structures and institutional recognition for those who work at the boundary of science and decision-making; increasing support through the USGCRP for research to develop decision support tools; and incorporating assessment of decision support resources for sectors and regions into the ongoing National Climate Assessment (NCA) process.**

Introduction

This chapter introduces decision-making frameworks that are useful for considering choices about climate change adaptation and mitigation. It focuses on the processes that promote sustained interaction between decision-makers and the scientific/technical community. The chapter reviews the state of knowledge and practice at each of the stages of an idealized collaborative decision support process – a process that includes steps such as defining the problem, identifying decision criteria, applying scientific information, evaluating response options, monitoring effectiveness, and revisiting the decision. Because of space limitations, the chapter does not assess specific decision support tools.

Climate conditions are changing (Ch. 2: Our Changing Climate), and historically successful strategies to manage climate-sensitive resources and infrastructure will become less effective over time. Decision-makers must increasingly make choices without full knowledge of the opportunities, risks, and underlying uncertainties. The sensitivity of the climate system to human activities, the extent to which mitigation policies are implemented, and the effects of other demographic, social, ecological, and economic changes on vulnerability also contribute to uncertainty in decision-making (de Chazal and Rounsevell 2009; Holling 2003).

Decision-makers routinely make complex decisions under uncertain conditions; they recognize that even though scientific information may be uncertain, it still provides valuable insights that will lead to better outcomes if incorporated into decision-making. Uncertainties can make decision-making in the context of climate change especially challenging for several reasons, including the rapid pace of changes in physical and human systems, the lags between climate change and observed effects, the high economic and political stakes, the number and diversity of potentially affected stakeholders, the need to incorporate scientific information of varying confidence levels, and value questions that arise (Mattson et al. 2012; NRC 2009). The social, economic, psychological, and political dimensions of these decisions underscore the need for ways, including improved communication of uncertain scientific information, to help decision-makers assess risks and opportunities associated with climate change. These include assisting with identification of climate risks and opportunities in government, business, community, family, and individual decisions.

Decision-makers often find accessing relevant and useful climate information to be a frustrating experience and request assistance with applying the daunting array of information sources and tools (ICATF 2010). Properly framing the issues, understanding the available options, establishing decision criteria, accessing relevant knowledge, and reaching decisions that have a good chance of being implemented are challenging in any case (Beratan and Karl 2012), but integrating scientific understanding of climate risks into specific sectoral and regional applications is daunting. An iterative decision process that incorporates constantly improving scientific information and learning through periodic reviews of decisions over time is helpful in the context of rapid changes in environmental conditions (NRC 2009, 2010c).

For some aspects of decision-making, tools and online information clearinghouses have been both scientifically validated and evaluated by users. Decision frameworks, tools, and processes can help improve decision-making in the context of climate variability and change. However, there are many unanswered questions about effective climate change decision-making that require research, including ways to evaluate the costs and benefits of alternative actions, ways to communicate relative amounts of risk associated with different options, consideration of the role of institutions and governance structures, and development and use of probabilistic forecasts of climate events in specific locations. Communication between scientists, decision-makers, and the public can be difficult and there are barriers to the use of existing tools; improvements in communications related to climate change and associated response options also need more research.

What are the decisions and who are the decision-makers?

There are many scales of decisions related to reducing climate impacts and multiple types of decision-makers. For example, the federal government is engaged in decisions that affect climate policy at the international level, but it also makes regulatory decisions (for example, setting efficiency standards for vehicles) and decisions on how to reduce risks associated with climate change within its own facilities and activities. State and local governments are involved in setting policy about both emissions and adaptation activities in a variety of applications, including land use, renewable portfolio and energy efficiency standards, and investments in resilience to extreme weather events. Many private-sector companies have initiated strategies to respond both to the risks to their investments and the business opportunities associated with preparing for a changing climate. Several non-governmental organizations have been active in supporting decisions that integrate both adaptation and mitigation considerations, often in the context of promoting sustainability within economic sectors, communities, and ecosystems. Finally, individuals make decisions on a daily basis that affect their preparedness for extreme events and the health and welfare of their families (NRC 2010a).

What is decision support?

Decision support refers to "organized efforts to produce, disseminate, and facilitate the use of data and information" to improve decision-making (NRC 2009). It includes processes, decision support tools, and services. Decision support processes are effective when they: 1) build relationships that can support longer-term problem-solving capacity between knowledge producers and users; 2) provide information that users regard as credible, useful, and actionable; and 3) enhance the quality of decisions (NRC 2009). Some examples of products and decision tools include scenarios of the future, assessments of impacts and vulnerability, maps of projected climate impacts, and data management and visualization tools. Decision support activities that facilitate well-structured decision processes can result in consensus about defining the problems to be addressed, objectives and options for consideration, criteria for evaluation, potential opportunities and consequences, and tradeoffs.

Using a Decision-making Framework

Creating well-structured, transparent, and collaborative decision processes involving researchers and stakeholders is as important to effective decision-making as having good scientific information and tools. An effective process will better enable decision-makers to apply complex information to decisions, consider uncertainties associated with climate variability and change, assess the wide range of possible human responses, and engage institutions and individuals who are potentially affected.

The National Research Council has concluded that an "iterative adaptive risk management" framework, in which decisions are adjusted over time to reflect new scientific information and decision-makers learn from experience, is appropriate for decisions about adaptation and ways to reduce future climate change, especially given uncertainties and advances in scientific understanding (NRC 2010a; Willows and Connell 2003). At its heart, iterative adaptive risk management is an approach used daily to make and update decisions, from personal judgments to complex management and policy choices. This process can be more difficult for complex decisions, which is why it is important to put in place institutions that incorporate adaptive management to assure that decisions can be updated as one gains experience and as new scientific information becomes available.

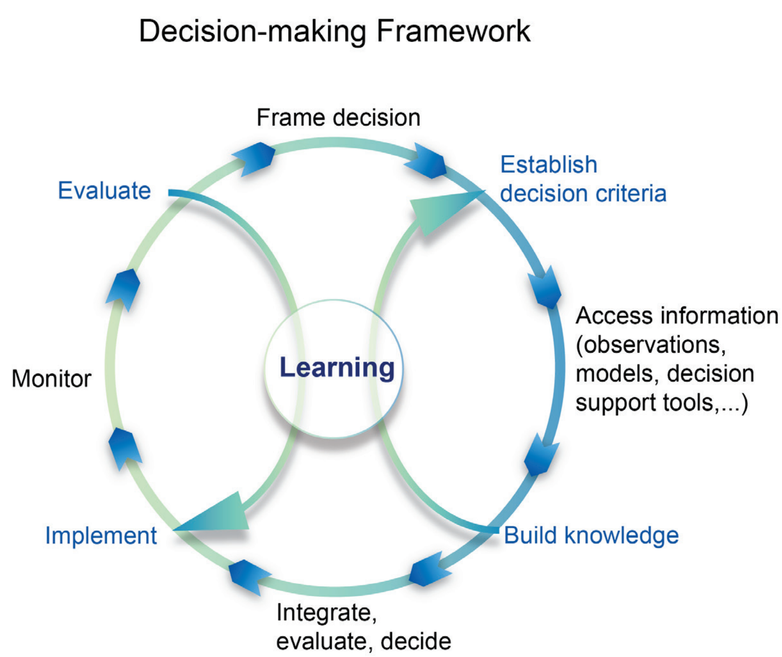

Figure 26.1: Decision-making Framework

Caption: This illustration highlights several stages of a well-structured decision-making process. Adapted from (NRC 2010a; Willows and Connell 2003).

Iterative risk management emphasizes "learning by doing" and continued adaptation to improve outcomes. Often, this process incorporates sustained interaction between decision-makers and the scientific/technical community. An idealized process includes: clearly defining the problem; establishing decision criteria; identifying and incorporating relevant information; evaluating options; and monitoring and revisiting effectiveness.

If the problem identified is to reduce the risks associated with climate change, decision criteria might include minimizing long-term costs and maximizing public safety. The relevant information might involve using scenarios to frame uncertainty in sea level rise and to understand how to translate that information into identifying property and ecosystems at risk.

Options to evaluate could include building levees or expanding coastal wetlands, which can absorb storm surges, including considerations of long- and short-term costs and effectiveness. After the decision is implemented, the effectiveness of the project and management practices can be revisited to ensure that the project continues to protect the community without damaging important habitat.

Scientific and technical information are important at many stages, but decisions about adaptation and ways to reduce future climate change also rest on non-scientific aspects, such as: personal or group values in the affected communities and within the business, government, or institution making the decisions; cultural and organizational characteristics; and other factors. Chapter 28: Adaptation addresses how some of these problems, including those that arise from decentralized decision-making with limited resources, might be addressed in the context of adaptation.

Problem Framing and Establishing Decision Criteria

An initial step in decision-making is to identify the context of the decision and factors that will affect choices – making sure that the questions are posed properly from scientific, decision-maker, and stakeholder (or public) perspectives. An important challenge is identifying the stakeholders in decision-making processes. There are often many categories of stakeholders, including those directly and indirectly affected by the outcomes of decisions as well as the decision-makers themselves, scientists, and elected officials. Other important issues often overlooked but critical to successful decision outcomes are:

- Understanding the goals and values of the participants in the decision process,
- Identifying risk perception and the sense of urgency of the parties involved in the decision,
- Being clear about the time frame of the decision (short- vs. long-term options relative to current and future risk levels) – and when the decision must be reached,
- Acknowledging the scale and degree of controversy associated with the risks and opportunities as well as the alternatives,
- Assessing the distribution of benefits or losses associated with current conditions and the alternatives being considered,
- Recognizing the diverse interests of the participants,
- Recognizing when neutral facilitators or trained science translators are needed to help with analysis, and
- Understanding legal or institutional constraints on options.

Based on the relevant objectives, decision criteria can be established that reflect constraints and values of decision-makers and affected parties. Criteria can be quantitative (for example, obtaining a particular rate of return on investment) or qualitative (for example, maintaining a community's character or culture). Decision framing and establishment of decision criteria can be facilitated using various methods, including brainstorming, community meetings, focus groups, surveys, and problem mapping. A variety of techniques for organizing and weighting information on multiple decision criteria are available, like multi-criteria analysis (Keeney and Raiffa 1993; Linkov and Moberg 2011).

Knowledge Building and Incorporating Scientific Information

Resource management and climate policy decisions often involve complex technical and scientific information. Ongoing conversations among scientists, decision-makers, and the public are often necessary to frame issues and identify, generate, and use relevant information (Scarlett 2010). Much scientific information is highly technical and may not be readily applied by non-experts. Thus, individuals, processes, and organizations that can help structure and sustain communication across different disciplines and communities are needed to effectively apply scientific knowledge in decision processes. Well-designed decision support processes, especially those in which there is a good match between the availability of scientific information and the capacity to use it, can result in more cost-effective outcomes based on relevant information that is perceived as useful and applicable. Unfortunately, the circumstances in which decision-makers, managers, and stakeholders can easily access the information they need in the context of evaluating climate-related risks and opportunities are limited. This leads to the need for assistance in crossing the boundary between science and applications; activities involved in bridging this gap to improve outcomes are often referred to as "boundary processes."

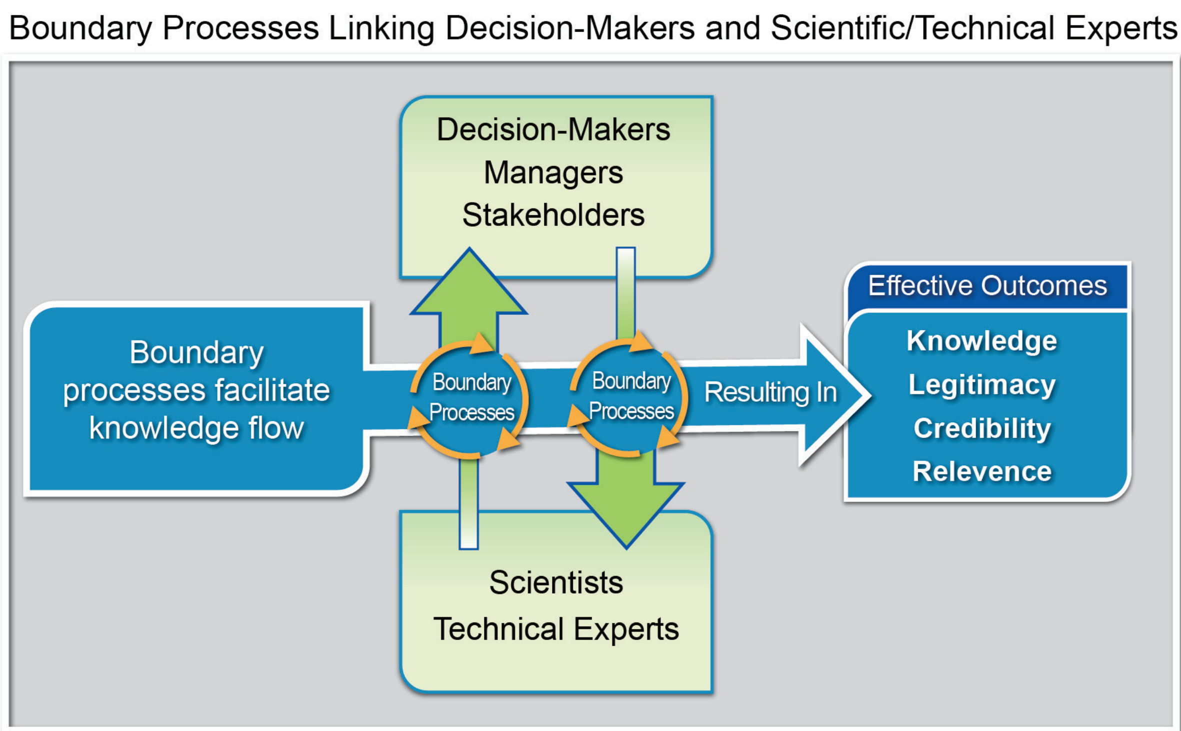

Figure 26.2: Boundary Processes Linking Decision-Makers and Scientific/Technical Experts

Caption: Boundary processes facilitate the flow of information and sharing of knowledge between decision-makers and scientists/technical experts. Processes that bring these groups together and help translate between different areas of expertise can provide substantial benefits. (Figure source: NOAA NCDC)

Regional and Sectoral Applications, Models, and Tools

Many decision support tools apply climate science and other information to specific decisions and issues; several online clearinghouses describe these tools and provide case studies of their use (for example, U.S. Climate Change Science Program (2005); Climate Adaptation Knowledge Exchange (2012), and the Ecosystem Based Management Tools Network (2012)). Typically, these applications integrate observed or modeled data on climate and a resource or system to enable users to evaluate the potential consequences of options for management, investment, and other decisions. These tools apply to many types of decisions that include, for example:

- *Water resources*: making water supply decisions in the context of changes in precipitation, increased temperatures and changes in water quality and water use (Means et al. 2010a; State of Washington 2012; Box 1: Denver Water case study; Ch. 3: Water Resources, especially the "Water Resources Management" section);
- *Infrastructure*: designing and locating energy or transportation facilities in the coastal zone to limit the impacts of sea level rise (See also Ch. 11: Urban Systems, Infrastructure, and Vulnerability and Ch. 10: Water, Energy, and Land Use);
- *Ecosystems and biodiversity*: managing carbon capture and storage, fire, invasive species, ecosystems and ecosystem services (Byrd et al. 2011; Labiosa et al. 2009; USGS 2012a, 2012b, 2012c) (Figure 3);
- *Human health*: providing public health warnings in response to ecosystem changes or degradation, air quality, or temperature issues (See also Ch. 9: Human Health).

Many available and widely applied decision-making tools can be used to support management of climate extremes or seasonal fluctuations of climate. Development of decision support resources focused on decadal or multi-decadal investment decisions is in a relatively early stage but is evolving rapidly and shared through the types of clearinghouses discussed above.

Florida Uses a Land-use Planning Tool

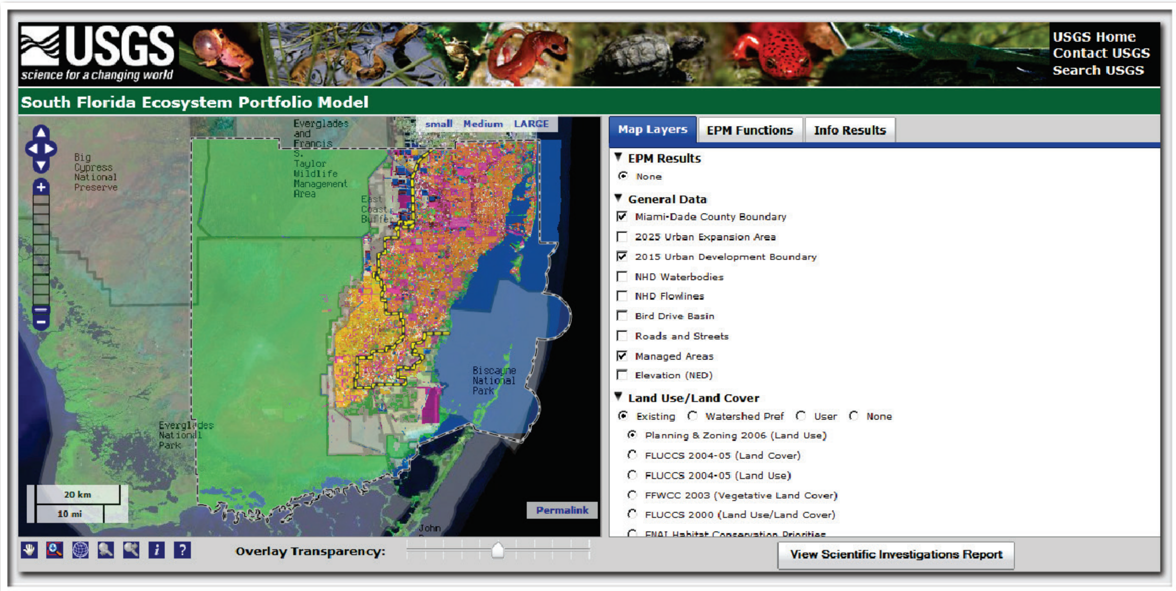

Figure 26.3: Florida Uses a Land-use Planning Tool.

Caption: The South Florida Ecosystem Portfolio Model (EPM) is a regional land-use planning tool that integrates ecological, economic, and social information and places that information in a context that is relevant to decision-makers and stakeholders. The EPM uses a multi-criteria evaluation framework that builds on Geographic Information Systems (GIS) analysis and spatially explicit models that characterize important ecological, economic, and societal consequences of regional land-use/cover change. Image from (USGS 2012).

Box 1: Denver Water Case Study

Climate change is one of the biggest challenges facing the Denver Water system. Due to recent and anticipated effects of climate variability and change on water availability, Denver Water faces the challenge of weighing alternative response strategies and is looking at developing options to help meet more challenging future conditions.

Denver Water is using scenario planning in its long-range planning process (looking out to 2050) to consider a range of plausible future scenarios. This approach contrasts with its traditional approach of planning for a single future based on demand projections, and should better prepare the utility and enhance its ability to adapt to changing and uncertain future conditions.

Denver Water is assessing multiple scenarios based on several potential water system challenges, including climate change, demographic and water use changes, and economic and regulatory changes. The scenario planning strategy includes "robust decision-making," which deliberately focuses on keeping as many future options open as possible while trying to ensure reliability of current supplies.

Scenario planning was chosen as a way to plan for multiple possible futures, given the degree of uncertainty associated with many variables, particularly demographic change and potential changes in precipitation. This method is easy to understand and has gained acceptance across the utility. It is a good complement to more technical, detailed analytical approaches.

The next step for Denver Water is to explore a more technical approach to test their existing plan and identified options against multiple climate change scenarios. Following a modified robust decision-making approach (Hall et al. 2012; Lempert et al. 2003), Denver Water will test and hedge its plan and options until those options demonstrate that they can sufficiently handle a range of projected climate conditions.

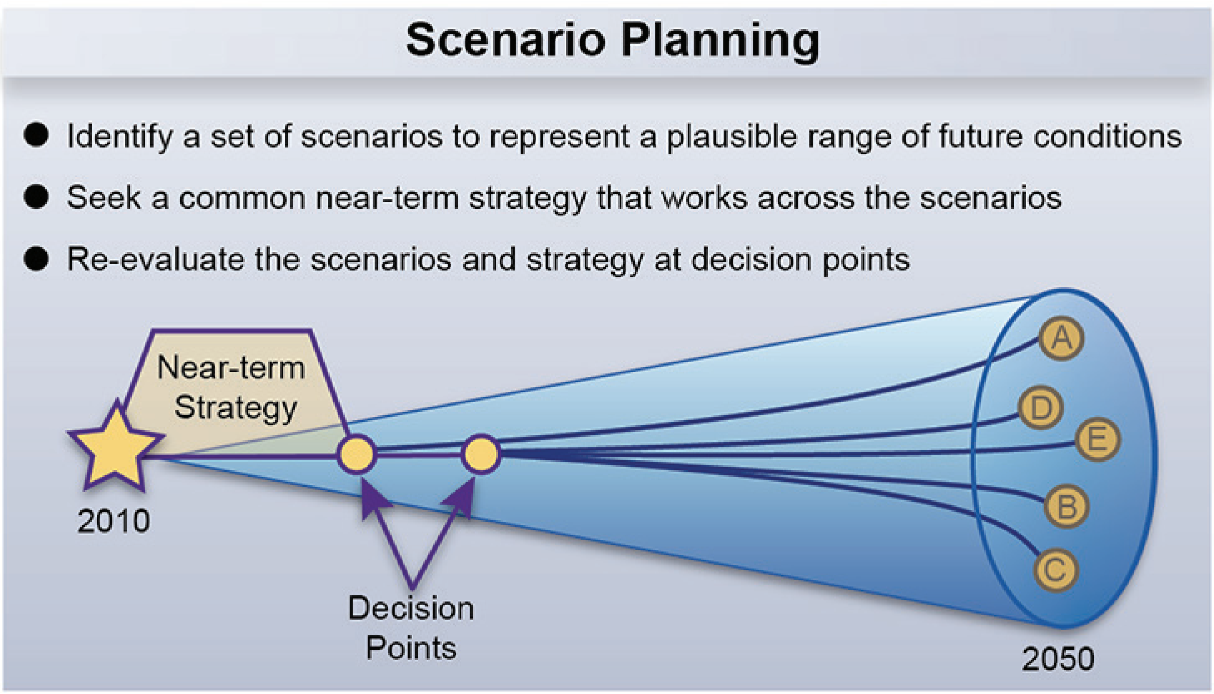

Figure 26.4: Scenario Planning

Caption: Scenario planning is an important component of decision-making. This "cone of uncertainty" is used to depict potential futures in Denver Water's scenario planning exercises. (Adapted from Waage, 2010, courtesy of Denver Water).

-- end box --

Value of Information

A frequently asked question when making complex decisions is: "When does the addition of more information contribute to decision-making so that the benefit of obtaining this information exceeds the expense of collecting and processing it?" In a decision context, the value of information often is defined as the expected additional benefit from additional information, relative to what could be expected without that information (Clemen and Reilly 1999; Williams et al. 2011; Yokota and Thompson 2004). Even though decision-makers often cite a lack of information as a rationale for not making timely decisions, delaying a decision to obtain more information doesn't always lead to different or better decisions (Fisher and Hanemann 1990; Hanemann 1989; Jacobs et al. 2005a; Jacobs et al. 2005b).

Assessing, Perceiving, and Managing Risk

At regional and sectoral levels, a changing and more variable climate generates both risks and opportunities. These positive and negative impacts can be evaluated using multiple criteria methods, valuation of both risks and opportunities, and scenarios. While a full quantitative risk analysis is not always possible or necessary, risk assessment provides a powerful framework for ranking risks and evaluating actions for managing them. The data from these assessments also illuminate how experts and the public can differ in their perception of risk. Understanding both risk assessment and risk perception proves important to managing risks of climate change. Using a risk-based approach is more appropriate for climate change than using cost-benefit analysis, because it incorporates uncertainty in the form of probabilities.

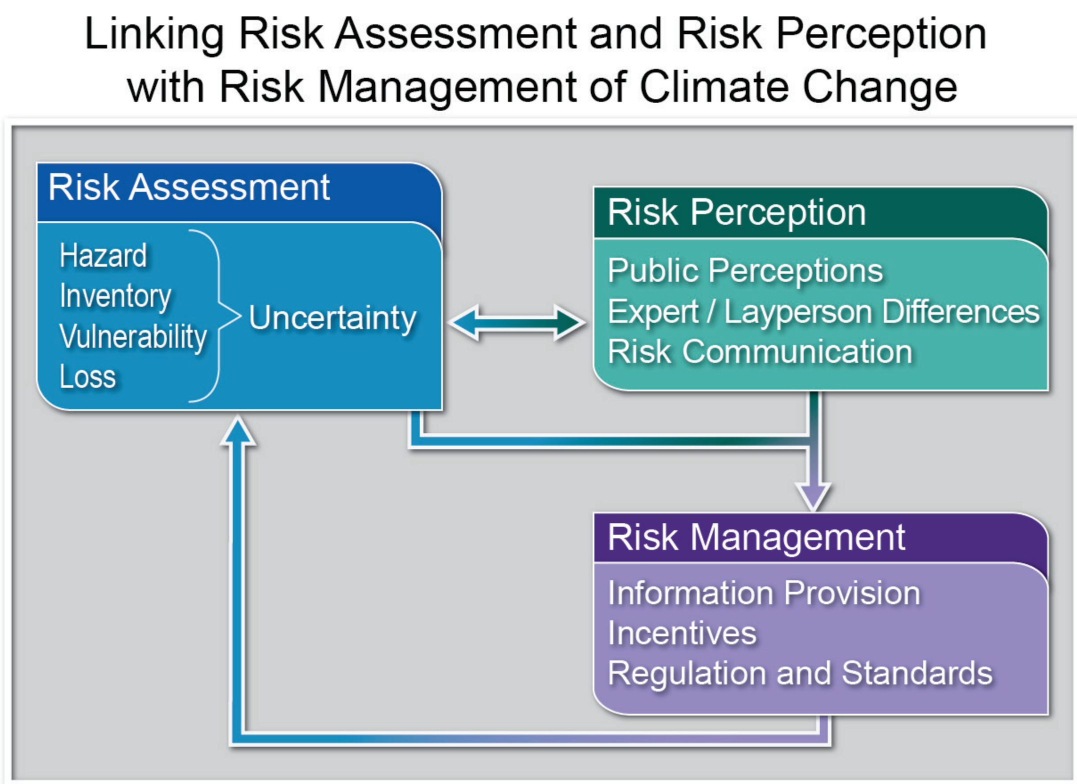

Figure 26.5: Linking Risk Assessment and Risk Perception with Risk Management of Climate Change.

Caption: This figure highlights the importance of incorporating both experts' *assessment* of the climate change risk and general public *perceptions* of this risk in developing risk management strategies. As indicated by the arrows, public perceptions of risk should be considered in expert risk assessment, which ideally helps the public to refine its understanding of the risks. Another crucial factor influencing risk perception is how risk is communicated. As the arrows indicate, risk management strategies should consider expert views and general public views of the risk, which will, in turn, affect the assessment and perception of climate change risk in the future.

Risk Assessment

Risk assessment includes studies that estimate the chances of specific sets of events occurring and/or their potential consequences (Haimes 1998). Experts often provide quantitative information regarding the nature of the climate change risk and the degree of uncertainty surrounding their estimates. Risk assessment focuses on the likelihood of negative consequences but does not exclude the possibility that there may also be beneficial consequences.

There are four basic elements for assessing risk – hazard, inventory, vulnerability, and loss (Grossi and Kunreuther 2005). This generalized approach to risk assessment is useful for a variety of types of decisions. The first element focuses on the risk of a *hazard* as a function of climate change, including interactions of climate effects with other factors. What is the likelihood of specific events occurring, and what is the uncertainty surrounding these estimates? The second element identifies the *inventory* of properties, people, and the environment at risk. To inventory structures, for instance, requires evaluating their location, physical dimensions, and construction quality. To evaluate the hazard and its impacts on inventory, it is useful to construct different climate change scenarios, the likelihood of their occurrence, and the uncertainty surrounding these estimates. Together, the hazard and inventory elements enable calculation of the damage *vulnerability* of the structures, people, and environment at risk.

The vulnerability component enables estimation of the human, property, and environmental *losses* from different climate change scenarios by integrating biophysical information on climate change and other stressors with socioeconomic and environmental information (Turner et al. 2003). These assessments typically involve evaluation of exposure, sensitivity, and adaptive capacity for current and projected conditions. Quantitative indicators are increasingly used to diagnose potential vulnerabilities under different scenarios of socioeconomic and environmental change (Eriksen and Kelly 2007; Moss et al. 2001) and to identify priorities and readiness for adaptation investments (Global Adaptation Institute 2012).

Risk Perception

Risk perception relates to the psychological and emotional factors that affect people's behavior. Social scientists and psychologists have studied people's concerns about risks (Leiserowitz 2010) and found that people view hazards with which they have little personal knowledge and experience as highly risky, and they especially dread them. In the case of unfamiliar technologies with catastrophic potential, such as nuclear power, members of the public often perceive the risks as much higher than experts do (Slovic 2000). The decision process of non-experts with respect to low-probability, high-consequence events differs from experts (Camerer and Kunreuther 1989).

People tend to focus on short time horizons, so future impacts from climate change are not given much weight in actions taken today. This tendency to ignore long-term impacts is one of the reasons that preparations for climate change are less likely to rise to the highest priority among some decision-makers (Kunreuther et al. 2012). This behavior highlights the importance of risk communication. Some of these challenges can be overcome by framing the risk in different ways. One way to convince individuals to pay attention to risk is to adjust the time horizon over which the probability of a loss is measured. For example, people are much more willing to take the risk seriously if they are told that the chance of at least one disaster is greater than 1 in 5 over a 25-year period rather than 1 in 100 in any given year (Weinstein et al. 1996).

Risk Management Strategies
Taking a broad, long-term perspective, risk management in a climate change context requires both mitigation and adaptation strategies (IPCC 2012; The World Bank 2010). In some cases, public agencies, private firms, and individuals already have sufficient incentives, information, and options available to adapt to emerging conditions. These options include ensuring continuity of service or fulfillment of agency responsibilities, addressing procurement or supply chain issues, preserving market share, or holding the line on agency or private-sector production costs. Commercially available mechanisms such as insurance can also play a role in providing protection against losses (Aerts and Botzen 2011). However, in some cases, these incentives and mechanisms are not sufficient, particularly for challenges outside the normal planning horizon of an agency or business. For example, the private sector faces challenges in providing coverage due to the uncertainty of the risks of climate change and liability issues associated with global climate change (Kunreuther and Michel-Kerjan 2007). In these cases, public sector involvement can make this adaptation process more effective. Such policies include public education programs, economic incentives (subsidies and fines), and regulations and standards. Private-public partnerships can be useful for communicating and setting priorities for managing climate change risks (Kunreuther 2002). Criteria for evaluating risk management strategies can include impacts on resource allocation, equity and distributional impacts, ease of implementation, and justification, among others.

Decision-makers' Toolkit

Many decision frameworks and tools are available to support and improve decision-making on climate change adaptation and ways to reduce future climate change.

A number of decision-making tools and processes generated by both the public and private sectors can assist stakeholders and decision-makers in meeting their own objectives, and can clarify where there are value differences or varying tolerances for risk and uncertainty. Several such tools are discussed here.

Comparative Tradeoff Methods
In making decisions, alternative options are often compared against some measure of the objectives. In such cases, approaches such as listing the pros and cons (Hammond et al. 2002), cost-benefit analysis (Boardman et al. 2005), multi-criteria methods (Clemen and Reilly 1999), or robust decision methods (Lempert and Groves 2010; Reeder and Ranger 2011) can be useful (see Box 2: Valuing the effects of different decisions). Multi-criteria methods provide a way to compare options by considering the positive and negative consequences for each of the objectives without having to choose a single valuation method for all the attributes important to decision-makers (Keeney and Raiffa 1993). This approach allows for consequences to be evaluated using criteria most relevant for a given objective (Keeney 2007). The options can then

be compared directly, by considering the relative importance of each objective for the particular decision.

Scenarios and Scenario Planning

Scenarios are not predictions, but are a means of gaining insight into the future and how actions may shape it. One approach to building scenarios begins with identifying any changes over time that might occur in climate and socioeconomic factors deemed relevant (for example, population growth and changes in water availability), and then using these projections to help decision-makers rank the desirability of alternative decision options to respond to these changes (Moss et al. 2010). This works well when decision-makers agree on framing and scientific evidence (Morgan et al. 2009; Sarewitz and Pielke Jr 2000). A second approach begins with a specific decision under consideration by a specific community of users and then poses questions relevant to these decisions (for example, "how can we build a vibrant economy in our community in light of uncertainty about population growth and water supply?") to organize information about future climate and socioeconomic conditions.

A relatively new use of scenarios combines quantitative science-based scenarios with "visioning" processes used by communities and organizations to explore desired futures, an approach known as "scenario planning" (Sheppard et al. 2011). This tool has been useful for water managers such as Denver Water, which has also used "robust decision-making" to assess policies that perform well across a wide range of future conditions, in the face of uncertainty and unknown probabilities (see Box 1: Denver Water case study). A variety of scenarios have been developed for the NCA, incorporating many of these approaches (see Ch. 1: Executive Summary).

Integrated Assessment Models

Integrated Assessment Models are tools for modeling interactions across climate, environmental, and socioeconomic systems (Patt et al. 2010; Weyant et al. 1996). They typically include representations of climate, economics, energy, and other technology systems, as well as demographic trends and other factors that can be used in uncertainty quantification. They are useful in national and global policy decisions about emissions targets, timetables, and the implications of different technologies for emissions management. These models are now being extended to finer resolutions and smaller scales to support regional decision-making.

Data Management Systems

Information technology systems and data analytics can harness vast data sources, making data more accessible to analysts and more useful for decision-makers. Such technologies allow for rapid scenario building and testing using many different variables so that the physical impacts of climate change can be more immediately and accurately measured (see Box 3: Data management). Similarly, information systems that synthesize data and products, such as the National Integrated Drought Information System (NIDIS) (2007) and the proposed National Climate Assessment Indicator System, (Janetos et al. 2012) can help to support mitigation and adaptation decisions.

Scientific Assessments

Ongoing assessments of the state of knowledge allow for iterative improvements in understanding over time, and the capacity to work directly with decision-makers to understand their needs for information (NRC 2007). A sustained assessment process (see Ch. 30: Sustained Assessment) can be deliberately designed to support the adaptation and mitigation information needs of decision-makers, with ongoing improvements in data quality and utility over time. Such ongoing assessment efforts that support decisions include the development and implementation of an end-to-end climate change indicator system (Janetos et al. 2012)

Box 2. Valuing the Effects of Different Decisions

Understanding costs and benefits of different decisions requires understanding people's preferences and developing ways to measure or "value" outcomes of those decisions relative to preferences. This "valuation" process is used to help rank alternative actions, illuminate tradeoffs, and enlighten public discourse (Keeney and Raiffa 1993). In the context of climate change, the process of measuring the value of different outcomes involves managers, scientists, and stakeholders and a set of methods to help decision-makers evaluate the consequences of climate change decisions (Nordhaus 2007; Stern 2007; Weitzman 2007). Although values are defined differently by different individuals and groups and can involve different metrics – for example, considering monetary versus non-monetary values (Boyd and Wainger 2002; Brown et al. 1995; Gregory et al. 2001), in all cases, valuation is used to assess the relative importance to the public or specific stakeholders of different impacts. Such valuation assessments can be used as inputs into iterative adaptive risk management assessments (which is advocated here because of its ability to robustly address uncertainty) or more traditional cost benefit analyses, if appropriate.

Some impacts ultimately are reflected in changes in the value of activities within the marketplace and in dollars (Mendelsohn 1998; Tol 2009) – for example, the impacts of increased temperatures on commercial crop yields (Cline 2007; Mendelsohn and Dinar 2009; Schlenker et al. 2006). Other valuations use non-economic metrics (Champ et al. 2003; EPA 2000; Freeman 2003; Kopp et al. 1997), such as considering the implications of melting Arctic sea ice on polar bear populations.

Valuation methods can provide input to a range of decision frameworks, including cost-benefit analysis of new or existing regulations (CBO 2009) or government projects (Boyd 2006; PCAST 2011); the implications of land use changes (Banzhaf et al. 2010; Irwin 2002); transportation investments and other planning efforts (Boyd and Banzhaf 2007; McConnell 1992); metrics for ecosystem services; and stakeholder and conflict resolution processes (Van den Belt 2004).

-- end box --

Box 3: Data Management

Decision Support Analysis (DSA), a general category of decision support tool, provides a framework for prioritizing actions in complex or crisis situations. State-of-the-art information technology systems and data analytics can harness vast and disparate data sources, making data more accessible to analysts and more useful for decision-makers. Information technologies that support DSA also make it possible to quickly and accurately measure current and projected physical impacts of climate change. This in turn can enable more effective decision-making, maximize disaster preparedness, and result in decisions that make infrastructure less vulnerable to risks.

With collaborative approaches to gathering and analyzing data, information can be displayed in real time by using both off-the-shelf and customized applications that can be deployed rapidly, either in response to catastrophes or in reaction to newly discovered risks and problems. This increases both the scale and the accessibility of available knowledge to decision-makers, and provides a fuller picture of a given situation as well as the capability to model the short- and long-term impacts of available options.

Recent examples demonstrate the potentially far-reaching effects of integrated, interoperable, data management systems. During the Deepwater Horizon oil spill in the Gulf of Mexico in 2010, the Sierra Nevada Corporation (SNC) created a "knowledge enterprise" system that incorporated data systems and data collection from more than 50 different federal agencies – coordinating, verifying, and centralizing into a single access point models, observations, evaluation of mitigation measures, and assessments of local needs and economic, environmental, and social concerns. This fusion of diverse data enabled decision-makers at national, state, and local levels to organize, sort, and analyze relevant information and ultimately helped to coordinate a comprehensive response. Another example involving Entergy (a regional utility), Swiss Re (a reinsurance company), and the Economics of Climate Adaptation working group integrated natural catastrophe weather models with economic data to predict a range of estimates related to climate change adaptation. This work represents the first comprehensive analysis of climate risks and adaptation economics along the U.S. Gulf Coast (America's Wetland Foundation 2012; Entergy 2012). In a third, a simplified model was developed, with support from the EPA, to look at flooding risks associated with coastal exposure in southern Maine (Gregg 2010; SLAWG 2012). Use of an "open platform" system that allows multiple users to input and access data resulted in spreadsheets, graphs, and 3D imagery displayed on contour maps downscaled to the city and county level for local decision-makers to access.

Technologies exist to solve the kinds of complex problems posed by evaluating, preparing for, and responding to climate-related impacts. The challenge is extending the availability of needed technology and ensuring the accessibility of relevant data, defining quality criteria, and identifying and filling data gaps.

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Keeping Pace with Scientific Advances

While decision support is not necessarily constrained by a lack of tools, a number of barriers restrict application of existing and emerging science and technology in adaptation and mitigation decisions (NRC 2009, 2010a, 2010d). Recent scientific developments could help to address some of these barriers, but are not yet incorporated into decision support tools (NRC 2006). For example, individual climate models can provide very different scenarios of future climate conditions for a given region, and the divergence of these projections can make it seem impossible to reach a decision. But comparing different models and constructing climate model "ensembles" can highlight areas of agreement across large numbers of models and model runs, and can also be used to develop ranges and other forms of quantification of uncertainty.

However, results from these activities are often difficult for researchers to access, let alone present in formats that could help decision-makers (Slocum et al. 2003)

Improving Decision Processes

Steps to improve collaborative decision processes could include training more "science translators" to help bridge science and decision-making; integrating development of decision support tools into fundamental scientific research; improving reward structures and institutional recognition for those who work at the boundary of science and decision-making; increasing support through the USGCRP for research to develop decision support tools; and incorporating assessment of decision support resources for sectors and regions into the ongoing National Climate Assessment (NCA) process.

The complexity, scope, and scale of climate change science further complicate our ability to apply science to decision-making. The challenges of communicating complex scientific information to decision-makers (including the public) are becoming increasingly clear (Pidgeon and Fischhoff 2011). But the challenges go beyond those of "translation" of complex information. The interface of science and decision-making includes defining and understanding the problem; identifying, generating, and using relevant technical and scientific information and analyses; and adjusting decisions as information and needs evolve. Defining the scope and scale of the relevant climate change problem can raise both scientific and social questions. Answering these questions requires scientific insights. But these questions also involve values and social constructs. This observation suggests the relevance of public engagement with technical experts and decision-makers in framing the problem and defining decision boundaries. It often requires that multiple participants engage in mutual learning and the co-production of relevant knowledge (Lee 1993). Some analysts have emphasized the importance of boundary processes that are collaborative and iterative (Curtin 2002, 2005). Boundary processes include, for example, joint fact finding and collaborative adaptive management, both of which engage scientists, stakeholders, and decision-makers in ongoing dialog about understanding the policy problem and identifying what information and analysis are necessary to evaluate decision options (Karl et al. 2007; McCreary et al. 2001). While use of these kinds of processes is increasing in decision settings involving complex scientific information and multiple, sometimes competing, societal values and goals, analysis of the conditions that contribute to their effectiveness is an emerging area of study (McCreary et al. 2001).

Many authors have noted that the ability to use data and tools has not kept pace with the rate at which new tools are developed. In this context, there is a need for "science translators" who can help decision-makers efficiently access and properly use data and tools that would be helpful in making more informed decisions in the context of climate change (Jacobs et al. 2005a; NRC 1999, 2008, 2009, 2010a, 2010b, 2010c; Snover et al. 2007). The culture of research in the U.S. also perpetuates a belief that basic and applied research need to be kept separate when it has been demonstrated that research motivated by "considerations of use" can also make fundamental advances in scientific understanding and theory (Stokes 1997). The U.S. climate research effort has been strongly encouraged to improve integration of social and ecological sciences and to develop the capacity for decision support to help address the need to effectively incorporate advances in climate science into decision-making (NRC 2011).

Implementation

The implementation phase of a well-structured decision process involves an ongoing cycle of setting goals, taking action, learning from experience, and monitoring to evaluate the consequences of undertaking specific actions. This cycle offers the potential for policy and outcome improvement through time. Ongoing evaluation can focus on how the system responds to the decision, leading to better future decisions, as well as on how different stakeholders respond, resulting in improvements in future decision-making processes. The need for social and technical learning to inform decision-making is likely to increase in the face of pressures on social and resource systems from climate change. However, the relative effectiveness of monitoring and assessment in producing social and technical learning depends on the nature of the problem, the amount and kind of uncertainty and risk associated with climate change, and the design of the monitoring and evaluation efforts.

Improving Decision Support

As they adjust to observed differences in climate and plan for uncertain future changes, decision-makers will face significant challenges because of uncertainties, a wide range of options, and the potentially extensive effects on numerous groups of stakeholders. Creating a well-structured, transparent, and inclusive decision process is vital and does not depend on additional scientific information.

However, there are a number of areas where scientific knowledge needs to be expanded or tools further developed to take advantage of existing insight, including:

- A comprehensive analysis of the state of decision support for adaptation and mitigation, including processes, tools, use, and successes/challenges, would be useful.
- Currently, the costs and benefits of non-market ecosystem goods and services (Boyd and Banzhaf 2007; EPA 2009; Heal 2000; Millennium Ecosystem Assessment 2005; NRC 2005) affected by mitigation and adaptation are inadequately understood, particularly those that have an impact over longer time scales.
- Improvements in risk management require closing the gap between expert and public understanding of risk, and building the institutions needed for managing persistent risks over the long term.
- Probabilistic forecasts or other information regarding consequential climate extremes/events have the potential to be very useful for decision-makers, if confidence in such forecasts can be improved.
- Improved communication among scientists, decision-makers, and the public regarding levels of scientific confidence and uncertainty in the context of specific decisions would be very useful in supporting risk management strategies.
- Currently, processes that effectively link scientists with decision-makers and the public in resource management settings are inadequate, and criteria to evaluate their effectiveness are not well-developed.

Traceable Accounts

Chapter 26: Decision Support

Key Message Process: During March-June 2012, the author team engaged in multiple technical discussions via teleconference (6 telecons) and email, and in a day-long in-person meeting (April 27, 2012 in Washington, DC). Authors reviewed over 50 technical inputs provided by the public and a wide variety of technical and scholarly literature related to decision support, including reports from the National Research Council that provided recent syntheses of the field [America's Climate Choices series, especially the report *Informing an effective response to climate change (NRC 2010a)*; *Informing Decisions in a Changing Climate* (NRC 2009)]. During the in-person meeting, authors reflected on the body of work informing the chapter and drafted a number of candidate critical messages that could be derived from the literature. Following the meeting, authors ranked these messages and engaged in expert deliberation via teleconference and email discussions in order to agree on a small number of key messages for the chapter.

Key message #1/3	**Creating well-structured, transparent, and collaborative decision processes involving researchers and stakeholders is as important to effective decision-making as having good scientific information and tools. An effective process will better enable decision-makers to apply complex information to decisions, consider uncertainties associated with climate variability and change, assess the wide range of possible human responses, and engage institutions and individuals who are potentially affected.**
Description of evidence base	Decisions about investment in adaptation and mitigation measures occur in the context of uncertainty and high political and economic stakes, complicating the evaluation of information and its application in decision-making (NRC 2009, 2010a). Decisions involve both scientific information and values—for example, how much risk is acceptable and what priorities and preferences are addressed (Mattson et al. 2012). At least as important as access to decision support tools is the creation of a well-structured and transparent decision process that involves affected parties in problem framing, establishing decision criteria, fact finding, deliberation, and reaching conclusions (Beratan and Karl 2012; NRC 2010a; Willows and Connell 2003). These aspects of decision-making are often overlooked by those who focus more on scientific inputs and tools, but given the high stakes and remaining uncertainties, they are crucial for effective decision-making on adaptation and mitigation. This message emphasizes that making a decision is more than picking the right tool and adopting its outcome. It is a process that should involve stakeholders, managers, and decision-makers to articulate and frame the decision, develop options, consider consequences (positive and negative), evaluate tradeoffs, make a decision, implement, evaluate, learn, and reassess (Beratan and Karl 2012; NRC 2010a). Often times having an inclusive, transparent decision process increases buy-in, regardless of whether a particular stakeholder's preferred option is chosen (NRC 2009).
New information and remaining uncertainties	N/A
Assessment of confidence based on evidence	N/A

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 26: Decision Support

Key Message Process: See key message #1.

Key message #2/3	**Many decision frameworks and tools are available to support and improve decision-making on climate change adaptation and ways to reduce future climate change.**
Description of evidence base	Many of these tools are developed to support adaptive management in specific sectors or for specific issues and include: risk assessments; GIS-based analysis products; targeted projections for high consequence events such as fires, floods, or droughts; vulnerability assessments; integrated assessment models; decision calendars; scenarios and scenario planning; and others (NRC 2009, 2010a; U.S. Climate Change Science Program 2005). Many of these tools have been validated scientifically and evaluated from the perspective of users. They are described in the sector or regional chapters of the assessment. In addition, a variety of clearing houses and data management systems provide access to decision support information and tools (for example, Climate Adaptation Knowledge Exchange ; Ecosystem Based Management Tools Network 2012). There are many tools, some of which we discuss in the chapter, that are currently being used to make decisions that include a consideration of climate change and variability, or the impacts or vulnerabilities that would result from such changes.
New information and remaining uncertainties	N/A
Assessment of confidence based on evidence	N/A

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: See key message #1.

Key message #3/3	**Steps to improve collaborative decision processes could include training more "science translators" to help bridge science and decision-making; integrating development of decision support tools into fundamental scientific research; improving reward structures and institutional recognition for those who work at the boundary of science and decision-making; increasing support through the USGCRP for research to develop decision support tools; and incorporating assessment of decision support resources for sectors and regions into the ongoing National Climate Assessment (NCA) process.**
Description of evidence base	There are many challenges in communicating complex scientific information to decision makers and the public (Pidgeon and Fischhoff 2011), and while "translation" of complex information is one issue, there are many others. Defining the scope and scale of the relevant climate change problem can raise both scientific and social questions, which require both scientific insights and consideration of values and social constructs, and that participants engage in mutual learning and the co-production of relevant knowledge (Lee 1993). Boundary processes that are collaborative and iterative (Curtin 2002, 2005), such as joint fact finding and collaborative adaptive management, foster ongoing dialogue and increasing understanding of policy problems and information and analysis necessary to evaluate decision options (Karl et al. 2007; McCreary et al. 2001). Analysis of the conditions that contribute to their effectiveness is an emerging area of study (McCreary et al. 2001). A large body of literature notes that the ability to use data and tools has not kept pace with the rate at which new tools are developed, pointing to a need for "science translators" who can help decision-makers efficiently access and properly use data and tools that would be helpful in making more informed decisions in the context of climate change (Jacobs et al. 2005a; NRC 1999, 2008, 2009, 2010a, 2010b, 2010c; Snover et al. 2007). The U.S. climate research effort has been strongly encouraged to improve integration of social and ecological sciences and to develop the capacity for decision support to help address the need to effectively incorporate advances in climate science into decision making (NRC 2011).
New information and remaining uncertainties	N/A
Assessment of confidence based on evidence	N/A

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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27. Mitigation

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Key Messages

1. **There are long time lags between actions taken to reduce carbon dioxide emissions and their effects on its atmospheric concentration. Mitigation efforts that only *stabilize* global emissions will therefore not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase.**
2. **To meet the rapid emissions reduction (B1) scenario used in this assessment, global mitigation actions would, within the next 25 years, need to limit global greenhouse gas emissions to a peak of around 44 billion tons of carbon dioxide per year. In 2011, global emissions were around 37 billion tons, and have been rising about 0.9 billion tons per year for the past decade. The world is therefore on track to exceed this level within a few years.**
3. **Over recent decades, the U.S. economy has emitted less carbon dioxide per dollar of gross domestic product (GDP) for many reasons. However, U.S. population and economic growth have outweighed these trends, and in the absence of additional public policies greenhouse gas emissions are expected to continue to rise.**
4. **Carbon storage in land ecosystems, especially forests, has offset around 13% of U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" is projected to become smaller as forests age.**
5. **Even absent a comprehensive national greenhouse gas policy, both voluntary activities and a variety of policies and means at federal, state, and local levels are currently in place that lower emissions. While these efforts represent significant steps towards reducing greenhouse gases, and often result in additional co-benefits,**

they are not close to sufficient to reduce total U.S. emissions to a level consistent with the B1 scenario analyzed in this assessment.

Mitigation refers to actions that reduce the human contribution to the planetary greenhouse effect. Mitigation actions include lowering emissions of greenhouse gases like carbon dioxide and methane, and particles that have a warming effect. Increasing the net uptake of carbon dioxide by land-use change and forestry can make a contribution as well. As a whole, the human contribution to emissions results in higher global concentrations of greenhouse gases and to a warming of the planet – and the effect is increased by various self-reinforcing cycles in the Earth system (such as the way melting sea ice results in more dark ocean water, which absorbs more heat, and leads to more sea ice loss). Also, the absorption of increased carbon dioxide by the oceans is leading to increased ocean acidity. Engineering a reduction of incoming solar radiation could limit the effect of increased greenhouse gas concentrations but would not help alleviate the acidity problem.

Four mitigation-related topics are assessed in this chapter. First, it presents an overview of greenhouse emissions and their climate influence, to provide a context for discussion of mitigation efforts. Second, the chapter provides an analysis of activities contributing to U.S. emissions of carbon dioxide and other greenhouse gases, considering both industrial and land-use activities. Third, it provides a summary of current government and voluntary efforts to manage these emissions of carbon dioxide and other greenhouse gases. Finally, there is an assessment of the adequacy of these efforts relative to the magnitude of the problem and a discussion of preparation for potential future action. While the chapter presents a brief overview of mitigation issues, it does not provide a comprehensive discussion of policy options, nor does it attempt to review or analyze the range of technologies available to reduce emissions. These topics have been the subject of other assessments, including those by the National Academy of Sciences (NRC 2010b) and the U.S. Department of Energy (US DOE 2011).

Emissions, Concentrations, and Climate Forcing

Setting mitigation objectives requires knowledge of the Earth system processes that determine the relationship among emissions, atmospheric concentrations and, ultimately, climate. Human-caused climate change results mainly from the increasing atmospheric concentrations of greenhouse gases (IPCC 2007). These gases cause radiative "forcing" – an imbalance of heat trapped by the atmosphere compared to an equilibrium state. Atmospheric concentrations of greenhouse gases are the result of the history of emissions and of processes that remove them from the atmosphere, for example by "sinks" like growing forests (Plattner et al. 2008). The fraction of emissions that remains in the atmosphere, which is different for each greenhouse gas, also varies over time as a result of Earth system processes.

The impact of greenhouse gases depends partly on how long each one persists in the atmosphere (Denman et al. 2007). Reactive gases like methane and nitrous oxide are destroyed chemically in the atmosphere, so the relationships between emissions and atmospheric concentrations are determined by the rate of those reactions. The term "lifetime" is often used to describe the speed with which a given gas is removed from the atmosphere. Methane has a relatively short lifetime (largely removed within a decade or so, depending on conditions), so reductions in emissions can lead to a fairly rapid decrease in concentrations as the gas is oxidized in the atmosphere

(Cicerone and Oremland 1988). Nitrous oxide has a much longer lifetime, taking more than 100 years to be substantially removed (IPCC 1995), so reductions in its emissions will take a longer time to affect its atmospheric concentration. Other gases in this category include industrial gases, like those used as solvents and in air conditioning, some of which persist in the atmosphere for hundreds or thousands of years.

Carbon dioxide (CO_2) is not reactive, so it does not, strictly speaking, have a "lifetime" (Moore and Braswell 1994). Instead, the relationship between emissions and concentrations year to year is determined by patterns of release (for example, through burning of fossil fuels) and uptake (for example, by vegetation and by the ocean) (Schimel 1995). Once CO_2 is emitted from any source, a portion is removed from the atmosphere over time by plant growth and absorption by the oceans, after which it continues to circulate in the land-atmosphere-ocean system until it is finally converted into stable forms in soils, deep ocean sediments, or other geological repositories.

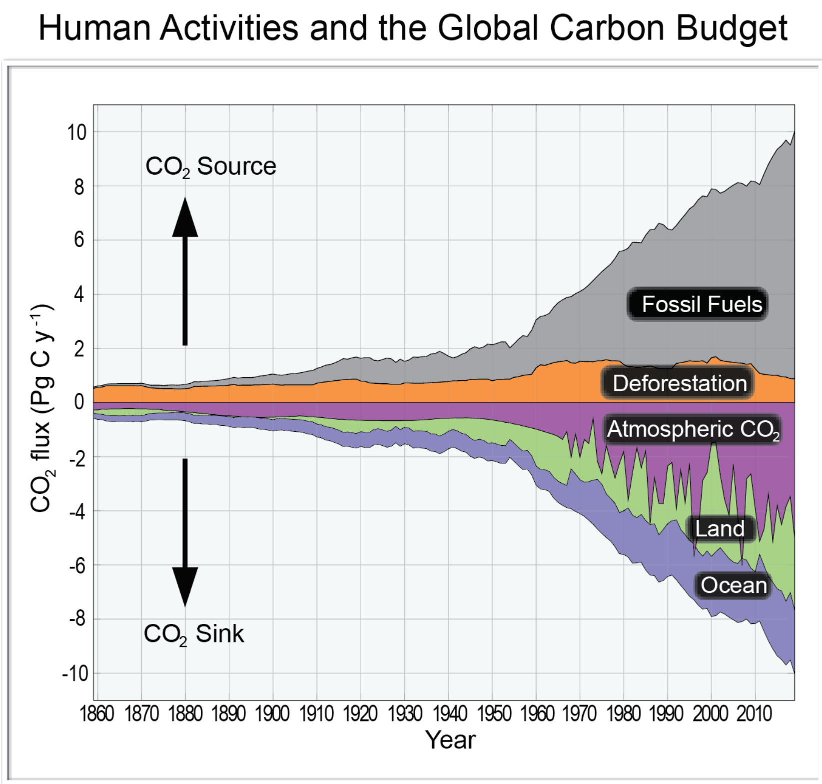

Figure 27.1: Human Activities and the Global Carbon Budget, 1859-2012.

Caption: Figure shows human-induced changes in the global carbon budget roughly since the beginning of the Industrial Revolution. Emissions from fossil fuel burning are the dominant cause of the steep rise in carbon dioxide shown here from 1950-present. (Canadell et al. 2007; Global Carbon Project 2011; Le Quere et al. 2009).

About half the carbon dioxide emitted at any one time is removed from the atmosphere in a century. However, around 20% of carbon released as emissions from fossil fuel burning continues to circulate and to affect atmospheric concentrations for thousands of years (Archer 2010). Stabilizing or reducing atmospheric carbon dioxide concentrations, therefore, requires very deep reductions in future emissions to compensate for past emissions that are still circulating in the Earth system. Avoiding future emissions, or capturing and storing them in stable geological storage, would prevent carbon dioxide from entering the atmosphere, and would have very long-lasting effects on atmospheric concentrations.

In addition to greenhouse gases, there can be climate effects from particulate matter in the atmosphere. An example is black carbon (soot), which is released from coal burning, diesel engines, cooking fires, wildfires, and other combustion sources. These particles have a warming influence, especially when they absorb solar radiation low in the atmosphere (Grieshop et al. 2009). Other particles, such as those formed from sulfur dioxide released during coal burning, have a cooling effect by reflecting some of the sun's radiation back to space, or by increasing the brightness of clouds.

The importance of each gas or type of particle is related to both how long it lasts in the atmosphere (the longer it lasts, the greater its influence) and its potency in trapping heat. The warming influence of different gases can be compared using "global warming potentials" (GWP), which combine these two effects, usually added up over a 100-year time horizon. GWPs are referenced to carbon dioxide—which is defined as having a GWP of 1.0— and the combined effect of multiple gases is denoted in carbon dioxide equivalents, or CO_2-e.

The relationship between emissions and concentrations can be modeled using Earth System Models (Plattner et al. 2008). Such models apply our understanding of biogeochemical processes that remove greenhouse gas emissions from the atmosphere to predict their future concentrations. These models show that stabilizing CO_2 emissions would allow atmospheric concentrations to increase approximately linearly, and would not stabilize its atmospheric concentration. Stabilizing atmospheric concentrations of CO_2 would require reducing emissions far below present-day levels. Concentration and emissions scenarios, such as the recently developed Representative Concentration Pathways (RCPs) and scenarios developed earlier by the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES), are used in Earth System Models to study potential future climates. The RCPs span a range of atmospheric targets for use by climate modelers (Moss et al. 2010; van Vuuren et al. 2006) as have the SRES cases. These global analyses form a framework within which the climate contribution of U.S. mitigation efforts can be assessed. In this report, special attention is given to the SRES A2 scenario (similar to RCP8.5), which assumes continued increases in emissions, and the SRES B1 scenario (close to RCP4.5), which requires a rapid reduction of emissions (Ch. 2: Our Changing Climate).

Box: Geoengineering

Geoengineering has been proposed as a third option for addressing climate change in addition to, or alongside, mitigation and adaptation. Geoengineering refers to intentional modifications of the Earth system as a means to address climate change. Two types of activities have been proposed: carbon dioxide removal (CDR), which boosts CO_2 removal from the atmosphere by various means, such as fertilizing ocean processes that help take up carbon; and solar radiation management (SRM, or sunlight reflection methods), which reflects a small percentage of sunlight back into space to offset warming from greenhouse gases (Shepherd 2009).

Current research suggests that SRM or CDR might diminish the impacts of climate change by reducing changes in temperature and precipitation. However, once undertaken, sudden cessation of SRM would exacerbate the climate effects on human populations and ecosystems, and some CDR might interfere with oceanic and terrestrial ecosystem processes (Russell et al. 2012). SRM undertaken by itself would not address additional rises in CO_2 atmospheric concentrations, and would therefore also fail to address ocean acidification. Furthermore, no international institutions exist to manage such a global intervention. The risks associated with such purposeful perturbations to the Earth system are thus poorly understood, suggesting the need for caution and comprehensive research, including consideration of the implicit moral hazards.

-- end box --

U.S. Emissions and Land-Use Change

Industrial Emissions

Aggregate U.S. industrial greenhouse gas emissions rose from just under 5,500 million tons CO_2-e in 1970 to 7,300 million tons CO_2-e in 2007, before falling in the 2009-2010 recession (EC-JRC/PBL 2011). Carbon dioxide made up just over 80% of these emissions, with methane (10%) and nitrous oxide (5%) second and third. Emissions of industrial gases (hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) grew slowly prior to 1994, but exhibit a marked acceleration thereafter because they are largely substitutes for ozone-destroying gases controlled by the Montreal Protocol (UNEP 2009).

Forty percent of carbon dioxide emissions are attributable to liquid fuels (petroleum), followed closely by solid fuels (principally coal), and to a lesser extent gaseous fuels such as natural gas (Marland et al. 2008). The two dominant sectors in producing these emissions are electric power generation (coal and gas) and transportation (petroleum). Flaring and cement manufacture together account for less than 2% of total emissions historically and less than 1% today.

The historical patterns of greenhouse gas emissions derive from four driving forces: rising population, per-capita gross domestic product (GDP) growth, a reduction in the energy needed to produce each unit of GDP, and a falling CO_2 content of energy. The decrease in energy intensity is associated with several changes in the economy: substitution responses to energy prices (such as substituting natural gas for coal as natural gas prices have declined); both autonomous and price-induced technological change to improve efficiency; and changes in the composition of the capital stock as well as the mix of sectors in the economy (Metcalf 2008; Sue Wing 2008). Over this period, emissions increased by 29%, resulting from growth in both population and output per person that outweighed reductions attributable to energy intensity and carbon intensity.

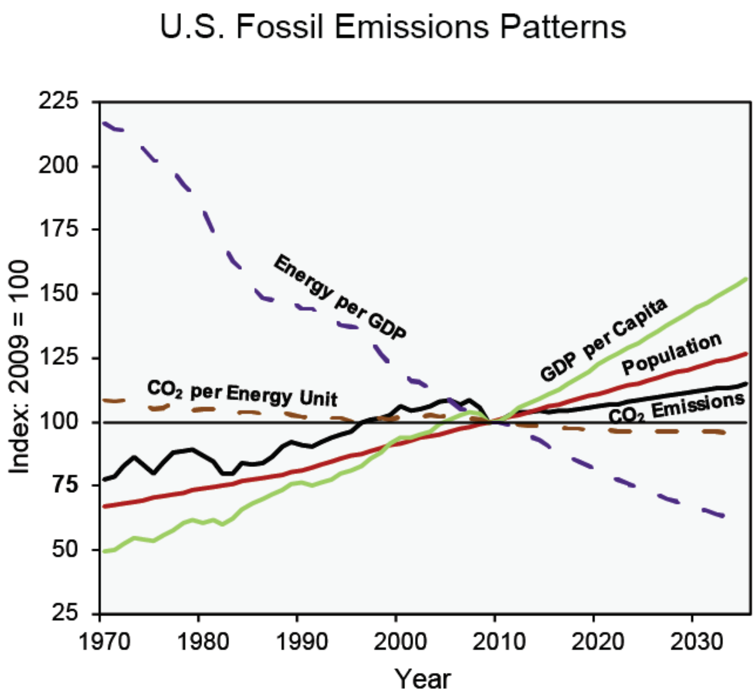

Figure 27.2. U.S. Fossil Emissions Patterns

Caption: While energy use as a percentage of gross domestic product has dropped significantly, total carbon dioxide emissions and population continue to rise. The chart shows observed patterns from 1970 to 2009, and forecasts through 2035. (Snead and Jones 2010).

These trends are expected to continue in the future, though more recent projections show a slower rate of emissions growth than the figure implies. Compared to 2010, projections for the year 2035 show 25% and 62% increases in population and per-capita GDP (respectively), a 42% decline in the energy-GDP ratio, and continued reductions in the emission intensity of energy use, with the net result being a 2% increase in energy-related CO_2 emissions over the period (EIA 2012)

Land Use & Agriculture

Estimates of carbon stocks and fluxes for U.S. lands are based on land inventories augmented with data from ecosystem studies and production reports (EPA 2010; USDA 2011). Stocks of the main carbon pools (biomass, dead wood, litter, soil, and harvested products) are estimated periodically and their rate of change, or flux, calculated as the average annual difference between two time periods.

U.S. lands were estimated to be a net sink of between approximately 640 and 1,074 million tons CO_2-e in the late 2000s (Pacala et al. 2007; USDA 2011). Estimates vary depending on choice of datasets, models, and methodologies (See Ch. 15: Biogeochemistry, Carbon Sink box for more discussion). This net land sink effect is the result of sources (from crop production, livestock production, and grasslands) and sinks (in forests, urban trees, and wetlands). Sources of carbon have been relatively stable over the last two decades, but sinks have been more variable. Long-term trends suggest significant emissions from forest clearing in the early 1900s followed by a sustained period of net uptake from forest regrowth over the last 70 years (Birdsey et al. 2006). The amount of carbon taken up by U.S. land sinks is dominated by forests, which have annually absorbed 7% to 24% (with a best estimate of about 13%) of fossil fuel CO_2 emissions in the U.S. over the past two decades.

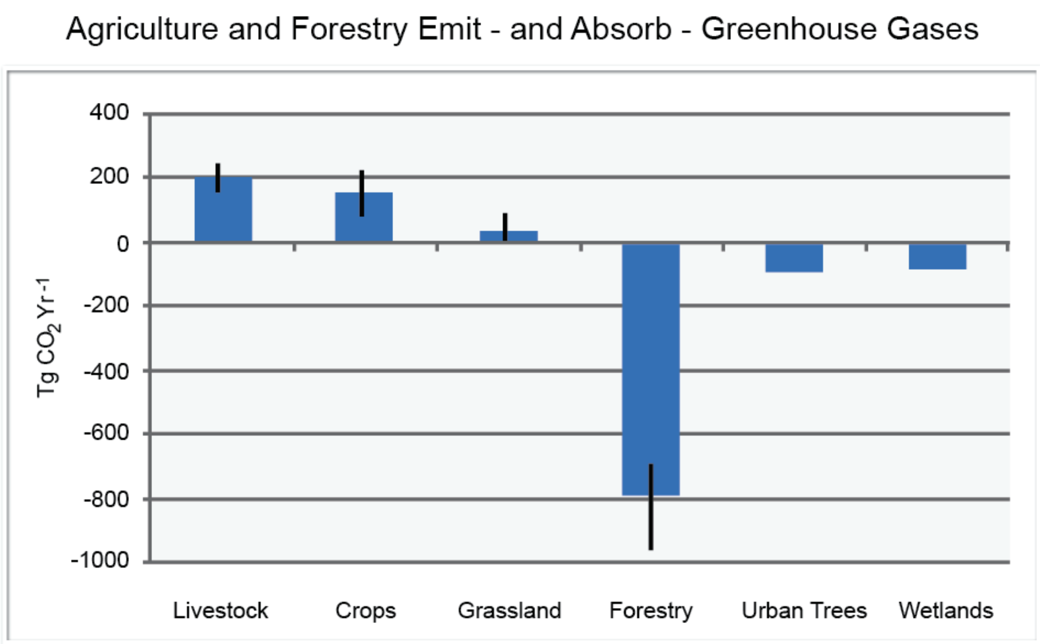

Figure 27.3: Agriculture and Forestry Emit – and Absorb – Greenhouse Gases

Caption: Chart shows greenhouse gas emissions from livestock and crop production, but does not include fossil fuels used in agricultural production. Forests are a significant "sink" that absorbs carbon dioxide from the atmosphere. (Pacala et al. 2007; USDA 2011).

The land sink, driven substantially by forest re-growth after agricultural land abandonment and recovery from harvesting, may not be sustainable for more than a few more decades (Pan et al. 2011; Williams et al. 2012). Deforestation continues to cause an annual loss of 877,000 acres (137,000 square miles) of forest land, offset by a larger area gain of new forest of about 1.71 million acres (268,000 square miles) annually (Masek et al. 2011). Since most of the new forest is on relatively low productivity lands of the Intermountain West, and much of the deforestation occurs on high productivity lands in the East, the net impact of recent land-use changes on carbon stocks is negative (Zheng et al. 2011). The effects of fertilization by increasing CO_2 concentration and nitrogen deposition are not likely to be as large as effects of land use and disturbances (Zhang et al. 2012). In some regions, longer growing seasons may increase annual productivity (Richardson et al. 2010). There is a lack of consistency in published results about the relative effects of disturbance and non-disturbance factors (for example, Caspersen et al. 2000; Pan et al. 2009; Zhang et al. 2012).

Droughts and other disturbances, such as fire and insect infestations, have already turned some U.S. land regions from carbon sinks into carbon sources (Zhang et al. 2012). The future persistence of the land sink depends on the relative effects of several interacting factors: recovery from historical land-use change, atmospheric CO_2 and nitrogen deposition, natural disturbances, and the effects of climate variability and change, particularly drought and effects on the length of the growing season.

Current Activities Affecting Emissions

Rapid and large reductions in global emissions would be necessary to reach the tighter targets (such as the B1 scenario; see Ch. 2: Our Changing Climate) analyzed in this assessment. Voluntary efforts and governmental actions in city, state, regional, and federal programs are underway that have the effect of reducing the U.S. contribution to total global emissions. Many, if not most, public programs affecting U.S. greenhouse gas emissions are designed to address other policy issues: energy, transportation, housing safety, and many others. Efforts directed specifically at greenhouse gas emissions include:

- Reduction in CO_2 emissions from energy end-use and infrastructure through the adoption of energy-efficient components and systems – including buildings, vehicles, manufacturing processes, and electric grid systems;
- Reduction of CO_2 emissions from energy supply through the promotion of renewables (wind, solar, bioenergy), nuclear energy, and coal and natural gas electric generation with carbon capture and storage, and
- Reduction of emissions of non-CO_2 greenhouse gases, for example, by lowering methane emissions from energy and waste, and cutting methane and nitrous oxide emissions from agriculture.

Federal Actions

The Federal government has implemented a number of measures that promote energy efficiency, clean technologies, and alternative fuels (The White House 2012; The White House 2010a, 2010b; DOE 2009b; GAO 2011). A sample is provided in Table 27.2. These actions fall into two general categories: research and development, to accelerate the development of innovative equipment and systems; and commercialization and deployment, including information dissemination, voluntary standards-setting, tax and other financial incentives, and rules and regulations.

At the national level, the Environmental Protection Agency has authority to regulate greenhouse gas emissions under the Clean Air Act. The Department of Energy provides most of the funding for energy research, development, and demonstration activities, and the Agency has the authority to regulate the efficiency of appliances and building codes for manufactured housing. In addition, most of the other federal agencies – importantly including Defense, Housing and Urban Development, Transportation, and Agriculture – have programs related to greenhouse gas mitigation.

City, State, and Regional Actions

Jurisdiction for greenhouse gases and energy policies is shared between the federal government and the states (for an overview see NRC 2010b). For example, states regulate economic activity and energy distribution, while the Federal Energy Regulatory Commission regulates wholesale sales and transportation of natural gas and electricity. In addition, many states have adopted climate initiatives as well as energy policies that reduce greenhouse gas emissions. For a survey of many of these state activities, see Table 27.1[1]. Many cities are taking similar actions.

The most ambitious is California's Global Warming Solutions Act (AB 32), which sets a state goal to reduce its greenhouse gas emissions to 1990 levels by 2020. The state program will cap emissions and use a market-based system of trading in emissions credits (cap-and-trade), as well as a number of regulatory actions. The most well-known, multi-state effort has been the Regional Greenhouse Gas Initiative (RGGI), formed by ten northeastern and mid-Atlantic states (though New Jersey exited in 2011). RGGI is a cap-and-trade system applied to the power sector with revenue from allowance auctions directed to investments in efficiency and renewable energy.

Voluntary Actions

A host of voluntary actions are being carried out by corporations, individuals, and non-profit organizations. Four examples give the flavor of the range of efforts:

- The Carbon Disclosure Project has the largest global collection of self-reported climate change and water-use information. The system enables companies to measure, disclose, manage, and share climate change and water use information. Some 650 U.S. signatories include banks, pension funds, asset managers, insurance companies, and foundations.
- Many local governments are undertaking initiatives to reduce greenhouse gas emissions within and outside of their organizational boundaries (Krause 2011; Pitt 2010). For example, over 1,055 municipalities from all 50 states have signed the U.S. Mayors Climate Protection Agreement (U.S. Mayors Climate Protection Agreement 2012), and many of these communities are actively implementing strategies to reduce their greenhouse gas footprint.

[1] For this paper version of the text, the entry page of the website is attached as a table.

- Under the American College and University Presidents' Climate Commitment (ACUPCC), 677 institutions have pledged to develop plans to achieve net-neutral climate emissions through a combination of on-campus changes and purchases of emissions reductions elsewhere.
- Federal voluntary programs include Energy STAR, a labeling program that identifies energy efficient products for use in residential homes and commercial buildings and plants, and programs and partnerships devoted to reducing methane emissions from fossil fuel production and landfill sources and high GWP emissions from industrial activities.

Box: Co-Benefits for Air Pollution and Human Health
Actions to reduce greenhouse gas emissions yield co-benefits for objectives apart from climate change, such as energy security and biodiversity. The co-benefits for reductions in air pollution have received particular attention. Because air pollutants and greenhouse gases share common sources, particularly in fossil fuel combustion, actions to reduce greenhouse gas emissions also reduce air pollutants. While some greenhouse gas measures might increase other emissions, broad programs to reduce greenhouse gases across an economy or a sector can reduce air pollutants markedly (Bell et al. 2008; van Vuuren et al. 2006).

There is significant interest in quantifying the air pollution and human health co-benefits of greenhouse gas mitigation, particularly from the public health community (World Health Organization and Davis 1997), as the human health benefits are immediate and local, in contrast to the long-term and widespread effects of climate change. Many of these studies have found that the monetized health and pollution control benefits could offset a significant portion of the direct mitigation cost (e.g., Burtraw et al. 2003). Methane reductions have also been shown to generate health benefits from reduced ozone, estimated to justify a 20% reduction of human-induced methane emissions (West et al. 2006). Similarly, in developing nations, reducing black carbon from household cook stoves has been shown to substantially reduce air pollution-related illness and death (Shindell et al. 2012; Wang and Smith 1999).

-- end box --

Preparation for Potential Future Mitigation Action

Current voluntary and governmental efforts do lower U.S. greenhouse gas emissions, but they are not close to sufficient to yield the U.S contribution to the reductions needed to meet the lower emissions scenario (B1) used in this assessment. The Annual Energy Outlook prepared by the DOE Energy Information Administration attempts to take account of these activities, yet it projects continued growth in energy-related U.S. CO_2 emissions through 2035 (EIA 2012). To meet the rapid emissions reduction (B1) scenario under reasonable assumptions about managing costs, annual *global* CO_2 emissions would need to peak at around 44 billion tons within the next 25 years or so and decline steadily for the rest of the century. The current U.S. share of global CO_2 emissions is about 20%. At the current rate of emissions growth, the world is on a track to exceed the 44 billion ton level within a decade (see Box). More aggressive greenhouse concentration targets, such as those associated with a frequently-discussed limit of a 2ºC (3.6ºF) temperature increase above pre-industrial levels (UFNCCC 2009) would require an even more dramatic reduction in global emissions (Webster et al. 2011).

Box: Emissions Scenarios and the RCPs

The Representative Concentration Pathways (RCPs) specify alternative limits to human influence on the Earth's energy balance, stated in watts per square meter (W/m^2) of the Earth's surface (Moss et al. 2010; van Vuuren et al. 2011b). The A2 emissions scenario used in this assessment implies atmospheric concentrations with radiative forcing slightly lower than the highest RCP, which is 8.5 W/m^2. The lower limits, at 6.0, 4.5 and 2.6 W/m^2, imply ever-greater mitigation efforts. The B1 scenario (rapid emissions reduction) also used in this assessment is close to the 4.5 W/m^2 RCP (Thomson et al. 2011) and to a similar case (Level 2) analyzed in a previous federal study (Clarke et al. 2007). Those assessments find that, to manage the economic costs, annual global fossil and industrial CO_2 emissions need to peak by 2035 to 2040 at around 44 billion tons of CO_2, and decline thereafter. The scale of the task can be seen in the fact that these global emissions were already at 37 billion tons in 2011, and for the past decade they have been rising at around 0.93 billion tons CO_2 per year (BP 2012). The lowest RCP would require an even more rapid turnaround and negative net emissions—that is, removing CO_2 from the air—in this century (van Vuuren et al. 2011b).

-- end box --

Achieving the B1 emissions path would require substantial decarbonization of the global economy by century's end, implying a fundamental transformation of the global energy system. Details of the energy mix along the way differ among analyses, but the implied involvement by the U.S. can be seen in a three-model study carried out under the U.S. Climate Change Science Program (Clarke et al. 2007). In this study, direct burning of coal without carbon capture is essentially excluded from the power system, and the same holds for natural gas toward the end of the century – to be replaced by some combination of coal or gas with carbon capture and storage, nuclear generation, and renewables. Biofuels and electricity are projected to substitute for oil in the transport sector. A substantial component of the task is accomplished with demand reduction, through efficiency improvement, conservation, and shifting to an economy less dependent on energy services.

The challenge is great enough even starting today, but delay by any of the major emitters makes meeting any such target even more difficult and may altogether rule out some of the more ambitious goals (Clarke et al. 2007). A study of the climate change threat and potential responses by the U.S. National Academies therefore concludes that there is "an urgent need for U.S. action to reduce greenhouse emissions" (NRC 2010a). The NRC goes on to suggest alternative national-level strategies that might be followed, including an economy-wide system of price penalties on greenhouse emissions and a portfolio of possible regulatory measures and subsidies. Deciding these matters will be a continuing task, and U.S. Administrations and the Congress face a long sequence of choices about whether to take additional mitigation actions, and how best to do it. Two supporting activities will help guide this process: opening future technological options and development of ever-more-useful assessments of the cost and effectiveness of policy choices.

Many technologies are potentially available to accomplish emissions reduction. They include: ways to increase the efficiency of fossil energy use and facilitate a shift to low-carbon energy sources; sources of improvement in the cost and performance of renewables (wind, solar, bioenergy) and nuclear energy; ways to reduce the cost of carbon capture and storage; and means to expand terrestrial sinks through management of forests and soils, and increased agricultural productivity (DOE 2011). In addition to the research and development carried out by private sector firms with their own funds, the federal government traditionally supports major programs to advance these technologies. This is accomplished in part by credits and deductions in the tax code, and in part by federal expenditure. For example, the 2012 federal budget devoted approximately $6 billion to clean energy technologies (OMB 2012). Success in these ventures, lowering the cost of greenhouse gas reduction, can make a crucial contribution to future policy choices (NRC 2010b).

Because they are in various stages of research and development, the costs and effectiveness of many of these technologies remain uncertain; continuing study of their performance is important to understanding their role in future mitigation decisions (Edmonds et al. 2000, 2007). In addition, evaluation of broad policies and particular mitigation measures requires frameworks that combine information from a range of disciplines. Study of mitigation in the near future can be done with energy-economic models that do not assume large changes in the mix of technologies or changes in the structure of the economy. Analysis over the time spans relevant to stabilization of greenhouse gas concentrations, however, requires Integrated Assessment Models, which consider all emissions drivers, and representations of how they are related to the larger economy and features of the climate system (Clarke et al. 2007; Clarke et al. 2009; Janetos et al. 2009; Prinn 2012; DOE 2009a). This type of analysis also is useful for exploring the relations between mitigation and measures to adapt to a changing climate.

Box: Interactions Between Adaptation and Mitigation

There are various ways in which mitigation efforts and adaptation measures are interdependent. For, example, the use of plant material as a substitute for petroleum-based transportation fuels, or directly as a substitute for burning coal or gas for electricity generation, has received substantial attention (for example, EIA 2012). But land that is used for mitigation purposes is potentially not available for food production, even as the global demand for agricultural products continues to rise (DeFries and Rosenzweig 2010; Melillo et al. 2009; Thomson et al. 2010). The converse of this is that land that is required for adaptation strategies, like setting aside wildlife corridors or expanding the extent of conservation areas, is potentially not available for mitigation involving the use of plant material, or active management practices to enhance carbon storage in vegetation or soils. These potential interactions are poorly understood but potentially important, especially as climate change itself affects vegetation and ecosystem productivity and carbon storage.

-- end box --

Continued development of these analytical capabilities can help support decisions about national mitigation and the U.S. position in international negotiations. In addition, as shown above, mitigation is being undertaken by individuals and firms as well as by city, state, and regional governments. For many of these efforts, the needed analysis of cost and effectiveness is limited, so additional support for studies of these activities is needed to insure that resources are efficiently employed.

Research Needs

- Development of cost-effective energy use technologies (devices, systems, and control strategies) and energy supply technologies that produce little or no CO_2 or other greenhouse gases.
- Better understanding of the relationship between emissions and atmospheric greenhouse gas concentrations is needed to more accurately predict how the atmosphere and climate system will respond to mitigation measures.
- The processes controlling the land sink of carbon in the U.S. require additional research, including analysis of economic decision-making about the fate of land and how it is managed, as well as the inherent ecological processes and how they respond to the climate system.
- Uncertainties in model-based projections of greenhouse gas emissions, and of the effectiveness and costs of policy measures, need to be better quantified. Exploration is needed of the effects of different model structures, assumptions about model parameter values, and uncertainties in input data.
- Social and behavioral science research is needed to inform the design of mitigation measures for maximum participation and to prepare a consistent framework for assessing costs and effectiveness of both voluntary mitigation efforts and regulatory and subsidy programs.

Table 27.1. State Climate and Energy Initiatives

STATE CLIMATE AND ENERGY INITIATIVES

Most states have implemented programs to reduce greenhouse gases (GHG's) or adopt increased energy efficiency goals. Examples of greenhouse gas policies include:

◙ Greenhouse Gas Reporting and Registries
http://www.c2es.org/us-states-regions/policy-maps/ghg-reporting

◙ Greenhouse Gas Emissions Targets
http://www.c2es.org/us-states-regions/policy-maps/emissions-targets

◙ CO_2 Controls on Electric Powerplants
http://www.edf.org/sites/default/files/state-ghg-standards-03132012.pdf

◙ Low-Carbon Fuel Standards
http://www.c2es.org/us-states-regions/policy-maps/low-carbon-fuel-standard

◙ Climate Action Plans
http://www.c2es.org/us-states-regions/policy-maps/action-plan

◙ Cap-and-Trade Programs
http://arb.ca.gov/cc/capandtrade/capandtrade.htm

◙ Regional Agreements
http://www.c2es.org/us-states-regions/regional-climate-initiatives#WCI

Also, states have taken a number of energy measures, motivated in part by greenhouse gas concerns. For example:

◙ Renewable Portfolio Standards
[http://www.dsireusa.org/documents/summarymaps/RPS_map.pdf]

◙ Energy Efficiency Resource Standards
http://www.dsireusa.org/documents/summarymaps/EERS_map.pdf

◙ Property Tax Incentives for Renewables
http://www.dsireusa.org/documents/summarymaps/PropertyTax_map.pdf

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Table 27.2. Sample Federal Mitigation Measures

Caption: A number of federal laws and regulations target ways to reduce future climate change by decreasing greenhouse gas emissions emitted by human activities

Greenhouse Gas Regulations
Emissions Standards for Vehicles and Engines -- For light-duty vehicles, rules establishing tightened standards for 2012-2016 model years and 2017-2025 model years. -- For heavy- and medium-duty trucks, a rule establishing standards for 2014-2018 model years.
Carbon Pollution Standard for New Power Plants -- A proposed a rule setting limits on CO_2 emissions from future power plants.
Stationary Source Permitting -- A rule setting GHG emissions thresholds for permits under the New Source Review Prevention of Significant Deterioration and Title V Operating Permit programs are required for new and modified industrial facilities.
Greenhouse Gas Reporting Program -- A program requiring annual reporting of GHG data from large emission sources and suppliers of products that emit greenhouse gases if released or combusted.
Other Rules and Regulations with Climate Co-benefits
Oil and Natural Gas Air Pollution Standards -- A rule revising New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants for certain components of the oil and natural gas industry.
Mobile Source Control Programs -- Particle control regulations affecting mobile sources, especially diesel engines, that reduce black carbon by controlling direct particle emissions. -- The requirement to blend increasing volumes of renewable fuels.
National Forest Planning -- Identify and evaluate existing information relevant to the plan area for a baseline assessment of carbon stocks. -- Reporting of net carbon stock changes on forest land is required.

Standards and Subsidies
<u>Appliance and Building Efficiency Standards</u> -- Energy efficiency standards and test procedures for residential, commercial, industrial, lighting, and plumbing products. -- Model residential and commercial building energy codes, and technical assistance to state and local governments, and NGOs.
<u>Financial Incentives for Efficiency and Alternative Fuels and Technology</u> -- Weatherization assistance for low-income households, tax incentives for commercial and residential buildings and efficiency appliances, and support for state and local efficiency programs. -- Tax credits for biodiesel and advanced biofuel production, alternative fuel infrastructure, and purchase of electric vehicles -- Loan guarantees for innovative energy or advanced technology vehicle production and manufacturing; investment and production tax credits for renewable energy production.
Support for Research, Development, Demonstration, and Deployment
-- Loan guarantees for innovative energy or advanced technology vehicle production and manufacturing; investment and production tax credits for renewable energy production.
Federal Agency Practices and Procurement
-- Executive orders and federal statutes requiring federal agencies to reduce building energy and resource consumption intensity, and to procure alternative fuel vehicles. -- Agency-initiated programs in most departments oriented to lowering energy cost and greenhouse gas emissions.

Traceable Accounts

Chapter 27: Mitigation

Key Message Process: Evaluation of literature by Coordinating Lead Authors

Key message #1/5	**There are long time lags between actions taken to reduce carbon dioxide emissions and reductions in its atmospheric concentration. Mitigation efforts that only *stabilize* global emissions will therefore not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase.**
Description of evidence base	The message is a restatement of conclusions derived from the peer-reviewed literature over nearly the past 20 years (see Section I of chapter). Publications have documented the long lifetime of CO_2 in the atmosphere, resulting in long time lags between action and reduction (Archer 2010; Schimel 1995), and Earth System Models have shown that stabilizing emissions won't immediately stabilize atmospheric concentrations, which will continue to increase (Plattner et al. 2008).
New information and remaining uncertainties	There are several important uncertainties in the current carbon cycle, especially the overall size, location, and dynamics of the land-use sink (Archer 2010; Schimel 1995). Simulating future atmospheric concentrations of greenhouse gases requires both assumptions about economic activity, stringency of any greenhouse gas emissions control, and availability of technologies, as well as a number of assumptions about how the changing climate system affects both natural and anthropogenic sources.
Assessment of confidence based on evidence	**Very High**. Observations of changes in the concentrations of greenhouse gases are consistent with our understanding of the broad relationships between emissions and concentrations.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: Please see KM #1 for description of process.

Key message #2/5	**To meet the rapid emissions reduction (B1) scenario used in this assessment, global mitigation actions would, within the next 25 years, need to limit global greenhouse gas emissions to a peak of around 44 billion tons per year. In 2011, global emissions were around 37 billion tons, and have been rising about 0.9 billion tons per year for the past decade. The world is therefore on track to exceed this level within a few years.**
Description of evidence base	A large number of emissions scenarios have been modeled, with a number of publications showing what would be required to limit CO_2 (Clarke et al. 2007; Moss et al. 2010; Thomson et al. 2011; van Vuuren et al. 2011a) to any predetermined limit. At current concentrations and rate of rise, the emissions of CO_2 would need to peak around 44 billion tons within the next 25 years in order to stabilize concentrations as in the B1 scenario. This limit is projected to be surpassed (BP 2012).
New information and remaining uncertainties	Uncertainties about the carbon cycle could affect these calculations, but the largest uncertainties are the assumptions made about the strength and cost of greenhouse gas emissions policies.
Assessment of confidence based on evidence	The confidence in the conclusion is **high**. This is a contingent conclusion, though – we do not have high confidence that this will actually occur, simply that if we do choose to limit concentrations as in the B1 scenario, emissions will need to peak soon and then decline.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 27: Mitigation

Key Message Process: Please see KM #1 for description of process.

Key message #3/5	**Over recent decades, the U.S. economy has emitted less carbon dioxide per dollar of GDP for many reasons. However, U.S. population and economic growth have outweighed these trends, and in the absence of additional public policies greenhouse gas emissions are expected to continue to rise.**
Description of evidence base	Trends in greenhouse gas emissions intensity are analyzed and published by governmental reporting agencies (EC-JRC/PBL 2011; EPA 2010; Marland et al. 2008; UNEP 2009; USDA 2011). Published, peer-reviewed literature cited in Section II of the Mitigation Chapter supports the conclusions about why these trends have occurred (Metcalf 2008; Sue Wing 2008), and government agency calculations support the statement about how population and economic growth are expected to counterbalance these trends (EIA 2012).
New information and remaining uncertainties	Economic forecasts are highly uncertain.
Assessment of confidence based on evidence	**High**. The statement is a summary restatement of published analyses by government agencies and interpretation from the reviewed literature.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: Please see KM #1 for description of process.

Key message #4/5	**Carbon storage in land ecosystems, especially forests, has offset around 13% of U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" is projected to become smaller as forests age.**
Description of evidence base	Underlying data come primarily from US Forest Service Forest Inventory and Analysis plots, supplemented by additional ecological data collection efforts. Modeling conclusions come from peer review literature. All references are in Section II of the Mitigation Chapter. Studies have shown that there is a large land-use carbon sink in the US (Birdsey et al. 2006; Pacala et al. 2007; USDA 2011). Many publications attribute this sink to forest re-growth, and the sink is projected to decline as a result of forest aging (Pan et al. 2011; Williams et al. 2012; Zhang et al. 2012) (Zheng et al. 2011) and factors like drought, fire, and insect infestations (Zhang et al. 2012) reducing the carbon sink of these regions.
New information and remaining uncertainties	FIA plots are measured extremely carefully over long time periods, but do not cover all US forested land. Other US land types must have carbon content estimated from other sources. Modeling relationships between growth and carbon content, and taking CO_2 and climate change into account have large scientific uncertainties associated with them.
Assessment of confidence based on evidence	**High**. Evidence of past trends is based primarily on government data sources, but these also have to augmented by other data and models in order to incorporate additional land-use types. Projecting future carbon content is consistent with published models, but these have intrinsic uncertainties associated with them.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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Key Message Process: Please see KM #1 for description of process.

Key message #5/5	**Even absent a comprehensive national greenhouse gas policy, both voluntary and governmental efforts to reduce emissions are under way. While these efforts have other co-benefits, they are not close to sufficient to reduce total U.S. emissions to a level consistent with the B1 scenario analyzed in this assessment**
Description of evidence base	The identification of state, local, regional, federal, and voluntary programs that will have an effect of reducing greenhouse gas emissions is a straightforward accounting of both legislative action and announcements of the implementation of such programs. Some of the programs include the Carbon Disclosure Project (CDP), the American College and University Presidents' Climate Commitment (ACUPCC), U.S. Mayors Climate Protection Agreement (U.S. Mayors Climate Protection Agreement 2012), and many other local government initiatives (Krause 2011; Pitt 2010). Several states have also adapted climate policies including California's Global Warming Solutions Act (AB 32) and the Regional Greenhouse Gas Initiative (RGGI). The assertion that they will not lead to a reduction of US CO_2 emissions is supported by calculations from the US Energy Information Administration.
New information and remaining uncertainties	There are no uncertainties about the existence of the programs identified. The major uncertainty in the calculation about future emissions levels is whether comprehensive national policy is implemented.
Assessment of confidence based on evidence	**Very High**. There is no uncertainty about whether programs exist or not, although there is recognition that their implementation may differ from how they are originally planned, and that institutions can always choose to leave voluntary programs (as is happening with RGGI, noted in the chapter). The statement about the future of US CO_2 emissions cannot be taken as a prediction of what will happen – it is a conditional statement based on an assumption of no comprehensive national legislation or regulation.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

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28. Adaptation

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Key Messages

1. **Substantial adaptation planning is occurring in the public and private sectors and at all levels of government, however, few measures have been implemented and those that have appear to be incremental changes.**
2. **Barriers to implementation of adaptation action include lack of funding, policy and legal impediments, and difficulty in anticipating climate-related changes at local scales.**
3. **There is no "one-size fits all" adaptation, but there are similarities in approaches across regions and sectors. Sharing best practices, learning by doing, and iterative and collaborative processes including stakeholder involvement, can help support progress.**
4. **Climate change adaptation actions often fulfill other societal goals, such as sustainable development, disaster risk reduction, or improvements in quality of life, and can therefore be incorporated into existing decision-making processes.**
5. **Vulnerability to climate change is exacerbated by other stresses such as pollution and habitat fragmentation. Adaptation to multiple stresses requires assessment of the composite threats as well as tradeoffs amongst costs, benefits, and risks of available options.**
6. **The effectiveness of climate change adaptation has seldom been evaluated, because actions have only recently been initiated, and comprehensive evaluation metrics do not yet exist.**

Introduction

Over the past few years, the focus on climate change has transitioned from the question "Is it changing?" to the equally important question: "Can society manage the unavoidable changes and avoid the unmanageable?" (Bierbaum et al. 2007; SEGCC 2007) Research indicates that both mitigation and adaptation are needed in order to minimize the damages from climate change and to adapt to the pace and ultimate magnitude of the changes that occur (McMullen and Jabbour 2009; ORNL 2012a, 2012b; Skaggs et al. 2012).

The study and application of adaptation to climate change is nascent compared to the many analyses of policies and practices to reduce emissions. Uncertainties about future socioeconomic conditions as well as future changes in climate can make it difficult to make some adaptation decisions now. However, the pace and magnitude of projected change emphasize the need for being prepared for a wide range and intensity of climate impacts. Because of the influence of human activities, the past climate is no longer a sufficient indicator of future conditions. Planning and managing based on the climate of the last century means that tolerances of some infrastructure and species will be exceeded (Kareiva 2008; ORNL 2012b; USGS 2012b). For example, building codes and landscaping ordinances will likely need to be updated not only for energy efficiency, but also to conserve water supplies, protect against disease vectors, reduce susceptibility to heat stress, and improve protection against extreme events (ORNL 2012b; Solecki and Rosenzweig 2012). Although there is uncertainty about future conditions, research indicates that actions can still be taken (Kerr 2011; NRC 2010a). Given that some uncertainties about how climate will change cannot be eliminated, development, refinement, and deployment of tools and approaches that enable decision-making and increase flexibility and robustness to climate change are still needed (PCAST 2011; Wilby and Dessai 2010; Ch. 2 Our Changing Climate).

Climate change affects human health, natural ecosystems, built environments, and existing social, institutional, and legal arrangements. Adaptation considerations include local, state, regional, national, and international jurisdictional issues. For example, in managing water supplies to adapt to a changing climate, the implications of international arrangements need to be considered in the context of managing the Great Lakes, the Columbia River, and the Colorado River to deal with drought (Garfin et al. 2012; Winkler 2012). Both "bottom up" community planning and "top down" national strategies may help regions deal with impacts such as increases in electrical brownouts, heat stress, floods, and wildfires. Such a mix of approaches will require cross-boundary coordination at multiple levels as operational agencies integrate adaptation planning into their programs.

Adaptation actions can be implemented reactively, after changes in climate occur, or proactively, to prepare for projected changes (NRC 2010a). Proactively preparing for climate change can reduce the harm from climate change, such as more intense extreme events, shifting zones for agricultural crops, and rising sea levels, while also facilitating a more rapid and efficient response to changes as they happen. This chapter highlights efforts at the federal, regional, state, tribal, and local levels, as well as initiatives in the corporate and non-governmental sectors to build adaptive capacity and resilience towards climate change. A map of illustrative adaptation activities and four-detailed case examples that highlight ongoing adaptation activity across the U.S. are provided in Sections II and IV of this chapter.

Adaptation Key Terms Definition Box*

Adapt, Adaptation: Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.

Adaptive Capacity: The potential of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, and to cope with the consequences.

Mitigation: Technological change and substitutions that reduce resource inputs and emissions per unit of output. Although several social, economic, and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks

Multiple Stressors: Stress that originates from different sources that affect natural, managed, and socioeconomic systems and can cause impacts that are compounded and sometimes unexpected. For example, when economic or market stress combines with drought to negatively impact farmers.

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Risk: A combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

*Definitions adapted from (IPCC 2007; NRC 2007, 2010a).

Adaptation Activities in the United States

1. Federal Government

Federal leadership, guidance, information, and support are vital to planning for and implementing adaptation actions at all scales and in all affected sectors of society (C2ES 2012b; CEQ 2011; NRC 2010a). Several new federal climate adaptation initiatives and strategies have been developed in recent years, including:

- Executive Order (EO) 13514 requiring federal agencies to develop recommendations for strengthening policies and programs to adapt to the impacts of climate change;
- The creation of an Interagency Climate Change Adaptation Task Force (ICCATF) that led to the development of national principles for adaptation and is leading to crosscutting and government-wide adaptation policies;

- The development of three crosscutting national adaptation strategies focused on integrating federal, and often state, local and tribal, efforts on adaptation in key sectors: the National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate, the National Fish, Wildlife and Plants Climate Adaptation Strategy (forthcoming); and a priority objective on resilience and adaptation in the National Ocean Policy Implementation Plan (forthcoming);

- A new decadal National Global Change Research Plan (2012–2021) that identifies the goals of improving basic science, informing decisions, improving assessments, and communicating and educating (USGCRP 2012); and

- The development of several interagency and agency-specific groups focused on adaptation, including a "community of practice" for federal agencies that are developing and implementing adaptation plans, an Adaptation Science Workgroup inside the U.S. Global Change Research Program (USGCRP); and several agency specific climate change and adaptation task forces.

Federal agencies are all required to plan for adaptation. Actions include coordinated efforts at the White House, regional and cross-sector efforts, agency-specific adaptation plans, as well as support for local-level adaptation planning and action.

Table 28.1: Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales*

Agency	Component	Action	Description
All Federal Agencies		Developing Adaptation Plans as part of their annual Strategic Sustainability Performance Plans	The 2012 Strategic Sustainability Performance Plans for 50+ Federal agencies contain specific sections on adaptation. Agencies are required to evaluate climate risks and vulnerabilities to manage both short- and long-term effects on missions and operations.
Department of Health and Human Services (HHS)	Centers for Disease Control and Prevention (CDC)	Climate-Ready States and Cities Initiative	Through their first climate change cooperative agreements in 2010, CDC awarded $5.25 million to ten state and local health departments to assess risks and develop programs to address climate change related challenges.
Department of Agriculture (USDA)		Integrating climate change objectives into plans and networks.	USDA is using existing networks such as the Cooperative Extension Service, the Natural Resource Conservation Districts, and the Forest Service's Climate Change Resource Center to provide climate services to rural and agricultural stakeholders.
USDA	Forest Service	Developed a *National Roadmap for Responding to Climate Change* and a *Guidebook for Developing Adaptation Options*, among many resources	The *National Roadmap* was developed in 2010 to identify short- and long-term actions to reduce climate change risks to the nation's forests and grasslands. The *Guidebook* (developed in 2011) builds on this previous work and provides science-based strategic and tactical approaches to adaptation. Other resources are available on the Forest Service website.
Department of Commerce (DOC)	NOAA	Supports research teams and local communities on adaptation-related issues and develops tools and resources.	Supports research teams such as Regional Integrated Sciences and Assessments (RISAs), which are partnerships with universities working collaboratively to inform resource management, planning, and policy. Established six regional climate centers (RCCs) to better assess and deliver regionally-focused climate science and services. Developed the Digital Coast partnership.
Department of Defense (DOD)	U.S. Army Corps of Engineers (USACE)	Developed a USACE climate change adaptation plan, and continues to update guidance for incorporating sea level rise into projects.	The Civil Works Program of the USACE released its climate change adaptation plan in 2011. The goal of the plan is to reduce vulnerabilities and improve resilience of water resources infrastructure impacted by climate change. The plan includes guidance on "Incorporating Sea-Level Change Considerations in Civil Works Programs."
DOD	Department of the Navy	Developed road maps for adaptation in the Arctic and across the globe.	The Navy Arctic Roadmap (November 2009) promotes maritime security and naval readiness in a changing Arctic. The Climate Change Roadmap (May 2010) examines broader issues of climate change impacts on Navy missions and capabilities globally.
Department of Energy (DOE)		Develop higher spatial and temporal scales of climate projections, and is working to integrate adaptation and climate considerations into integrated assessments.	Develops community-based, high-resolution (temporal and spatial) models for climate projections and integrated assessment models that-increasingly reflect multi-sectoral processes and interactions, multiple stressors, coupled impacts, and adaptation potential.

Department of the Interior (DOI)	**Fish and Wildlife Services (FWS)**	**Developed a FWS climate change strategic plan. Established a network of Landscape Conservation Cooperatives.**	**The FWS climate change strategy plan (September, 2010) establishes a basic framework to help ensure the sustainability of fish, wildlife, plants, and habitats in the face of climate change. In 2009 DOI established a network of 22 Landscape Conservation Cooperatives (LCCs) designed to promote shared conservation goals, approaches, and resource management planning and implementation across the United States, including Alaska, Hawaii, and the Caribbean.**
DOI	U.S. Geological Survey (USGS)	Established a network of Climate Science Centers (CSCs).	DOI operates a National Climate Change and Wildlife Center and eight regional CSCs, which provide scientific information and tools that land, water, wildlife, and cultural resource managers and other stakeholders can apply to anticipate, monitor, and adapt to climate change.
Department of Transportation (DOT)	Federal Highway Administration (FHWA)	Developed Risk Assessment Model for transportation decisions.	DOT worked with five local and state-level transportation authorities to develop a conceptual Risk Assessment Model to help transportation decision makers identify which assets are: a) most exposed to the threats from climate change and/or b) associated with the most serious potential consequences of climate change threats. Completed in November 2011.
DOT		Comprehensive study of climate risks to transportation infrastructure in the Gulf Coast Region, followed by an in-depth study for Mobile, Alabama.	Phase 1 of the study (completed in 2008) assessed the vulnerability of transportation infrastructure to climate change impacts across the Gulf region. Phase 2, expected to be completed in 2013, is focused on Mobile, Alabama. The effort is designed to develop transferable tools that will help transportation planners across the country.
Environmental Protection Agency (EPA)		Developed Climate Ready Estuaries and Climate Ready Water Utilities Working Group. Developed a draft EPA water program adaptation strategy.	The Climate Ready Estuaries program works with coastal managers to: 1) assess vulnerabilities; 2) develop and implement adaptation strategies; 3) engage stakeholders; and 4) share lessons learned. The Climate Ready Water Utilities initiative provides resources and tools to assist the water sector in adapting to climate change. The Draft *National Water Program Strategy: Response to Climate Change* addresses climate change impacts on water resources and EPA's water programs.
National Aeronautics and Space Administration (NASA)		NASA's Climate Adaptation Science Investigator (CASI) Workgroup was initiated to engage NASA climate modelers, scientists, engineers, and NASA institutional stewards to explore climate impacts and adaptation strategies for NASA research centers and facilities.	The team leverages internal NASA technical capabilities and resources to build capacity to address climate change, and has engaged in a range of activities since CASI's launch in the summer of 2010, including: 1) downscaling NASA center and facility-specific climate hazard information and projections; 2) conducting climate research customized to the needs of each location; 3) building inventories of each facility and center's existing climate and impact data and research activities; and 4) coleading adaptation workshops

*This list contains selected examples of agency work on adaptation and should not be considered all-inclusive. Material provided in table is derived from Agency websites.

Federal agencies can be particularly helpful in facilitating climate adaptation by:

- Fostering the stewardship of public resources and maintenance of federal facilities, services, and operations such as defense, emergency management, transportation, and ecosystem conservation in the face of a changing climate (NPS 2010; NRC 2010a; Rosenzweig and Horton 2012; Smith et al. 2010);
- Providing usable information and financial support for adaptation (NRC 2010a; Smith et al. 2010);
- Facilitating the dissemination of best practices and supporting a clearinghouse to share data, resources, and lessons learned (National Climate Adaptation Summit Committee 2010; NRC 2010a);
- Dealing with and anticipating impacts that cross geopolitical boundaries and supporting flexible regulatory frameworks (NRC 2010a; Smith et al. 2010);
- Ensuring the establishment of federal policies that allow for “flexible” adaptation efforts and do not lead to unintended consequences (OTA 1993; Smith et al. 2010); and
- Building public awareness (CEQ 2010).

2. States

States have become important actors in national climate-related efforts, often through the creation of policies and programs that incentivize or inhibit adaptation at other governance scales (Goulder and Stavins 2011; Morsch and Bartlett 2011); through regulation; and by serving as laboratories for innovation (Feldman and Kahan 2007; Moser 2009). Although many of these actions are not specifically designed to address climate change, they often include climate adaptation components.

Many of the climate-specific adaptation actions at the state-level focus on planning. As of winter, 2012, at least 15 states have completed climate adaptation plans; four states are in the process of writing their plans; and seven states have made recommendations to create state-wide adaptation plans (C2ES (Center for Climate and Energy Solutions) 2012a).

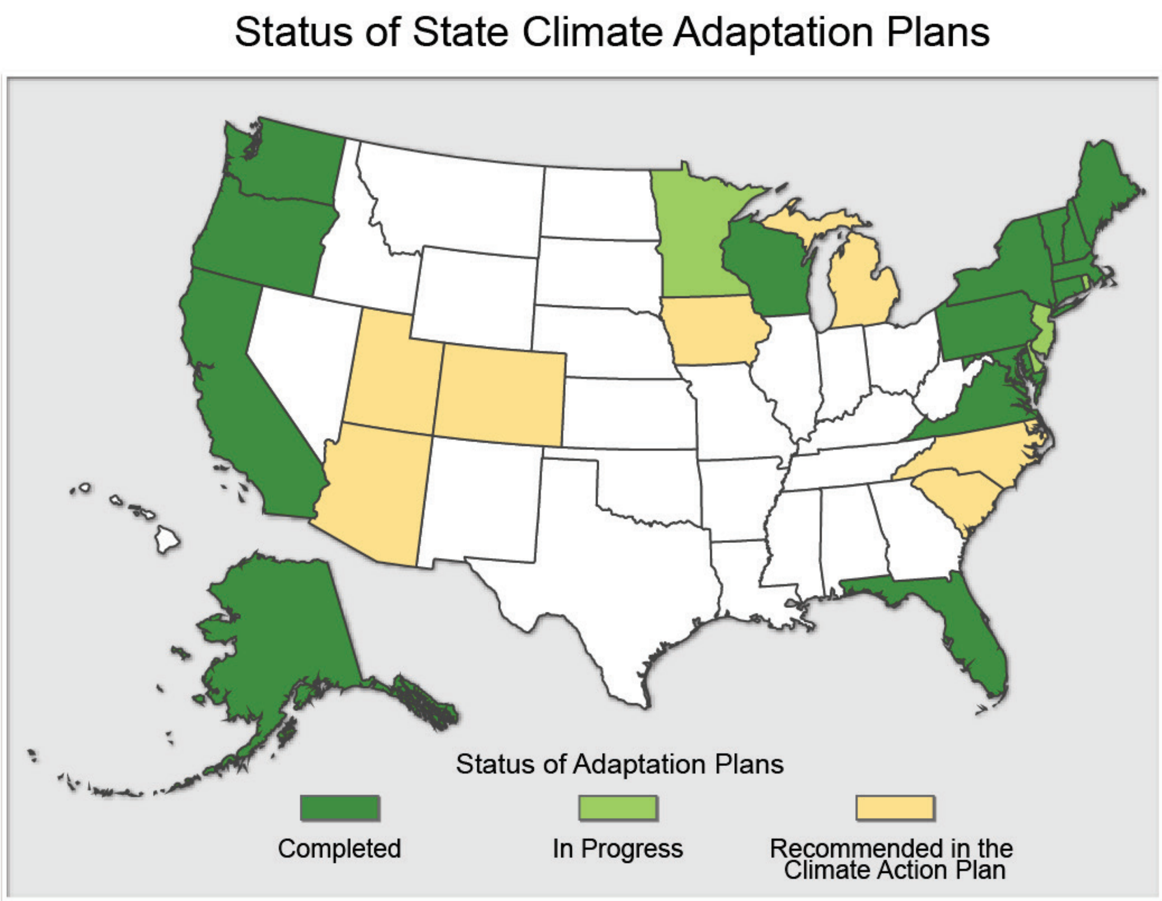


Figure 28.1 Status of State Climate Adaptation Plans. (Figure redrawn from C2ES (Center for Climate and Energy Solutions) 2012a)

In addition to formal adaptation plans, numerous states have created sector-specific plans that consider long-term climate change. For example, at least 16 states have biodiversity conservation plans that focus on preparing for long-term changes in climate (AFWA 2011). In addition to planning, some states have created legislation and/or programs that are either directly or indirectly targeted at reducing state-relevant climate vulnerabilities.

Table 28.2: Examples of State-Level Adaptation Activities

State	Adaptation Action
Alaska	Alaska Climate Change Impact Mitigation Program provides funds for hazard impact assessments to evaluate climate change related impacts, such as coastal erosion and thawing permafrost (Immediate Action Workgroup 2008).
California	Building standards mandating energy and water efficiency savings, advancing both adaptation and mitigation; State Adaptation Plan calls for 20% reduction in per capita water use (EPA 2012).
Florida	Law supporting low water use landscaping techniques (Salkin 2009).

Hawaii	Water code that calls for integrated management, preservation, and enhancement of natural systems (Marra 2012).
Kentucky	*Action Plan to Respond to Climate Change in Kentucky: A Strategy of Resilience,* which identifies six goals to protect ecosystems and species in a changing climate.
Louisiana	*Comprehensive Master Plan for a Sustainable Coast 2012* includes both protection and restoration activities addressing land loss from sea level rise, subsidence, and other factors over the next 50 years (State of Louisiana 2012).
Maine	The *Maine Sand Dune Rules* require that structures greater than 2,500 square feet be set back at a distance that is calculated based on the future shoreline position and considering two feet of sea level rise over the next 100 years (Grannis 2011).
Maryland	Passed *Living Shorelines Act* to reduce hardened shorelines throughout the state (Feifel 2010); passed “Building Resilience to Climate Change” policy which establishes practices and procedures related to facility siting and design, new land investments, habitat restoration, government operations, research and monitoring, resource planning, and advocacy.
Montana	Maintains a statewide climate change website to help stakeholders access relevant and timely climate information, tools, and resources.
New Mexico	The Active Water Resource Management program allows for temporary water rights changes in real time in case of drought (Propst 2012).
Pennsylvania	Enacted polices to encourage the use of green infrastructure and ecosystem based approaches for managing storm water and flooding (Solecki and Rosenzweig 2012).
Rhode Island	Requires public agencies considering land-use applications to accommodate a 3 to 5 foot rate of sea level rise.
Texas	Coordinated response to drought through National Integrated Drought Information System (NIDIS); RISAs (Southern Climate Impacts Planning Program [SCIPP], Climate Assessment for the Southwest [CLIMAS]); and state and private sector partners through anticipatory planning and preparedness (for example, implemented in 2011 drought) (SCIPP 2012).

3. Tribal Governments

Tribal governments have been particularly active in assessing and preparing for the impacts of climate change. For example:

- Adaptation planning in Point Hope, Alaska, emphasizes strategies for community health (Brubaker et al. 2010).
- In Newtok, Alaska, the village council is leading a land-acquisition and planning effort to relocate the community, because climate-induced coastal erosion has destroyed essential infrastructure, making the current village site unsafe (Bronen 2011).
- The Tulalip Tribes in Washington State are using traditional knowledge gleaned from elders, stories, and songs and combining this knowledge with downscaled climate data to inform decision-making (Simmonds 2011). Also in Washington State, the Swinomish Indian Tribal Community integrated climate change into decision-making in major

sectors of the Swinomish Community, such as education, fisheries, social services, and human health (Lamb 2011).

- The Haudenosaunee Confederacy in the northeastern U.S. is addressing climate impacts by preserving a native food base through seed-banking (Simmonds 2011; Ch. 12: Tribal Lands and Resources).

4. Local and Regional Governments

Most adaptation efforts to date have occurred at local and regional levels (Anguelovski and Carmin 2011; Gregg et al. 2011; Rabe 2009; Wallis 2011; Wheeler 2008). Primary mechanisms that local governments are using to prepare for climate change include: land-use planning; provisions to protect infrastructure and ecosystems; regulations related to the design and construction of buildings, roads, and bridges; and emergency preparation, response, and recovery (Dierwechter 2010; Grannis 2011; Kahn 2009; Selin and VanDeveer 2007; Solecki and Rosenzweig 2012).

According to a recent survey of 298 U.S. local governments, 59% indicated they are engaged in some form of adaptation planning (Carmin et al. 2012). Local adaptation planning and actions are unfolding in municipalities of varying sizes and in diverse geographical areas. Communities such as Keene, New Hampshire; New York City, New York; King County, Washington; and Chicago, Illinois are vanguards in the creation of climate adaptation strategies (Binder et al. 2010; NRC 2010a; Solecki and Rosenzweig 2012). In addition to local government action, regional agencies and regional aggregations of governments are becoming significant climate adaptation actors (USGS 2012b; Wallis 2011).

Table 28.3: Examples of Local and Regional Adaptation Activities

Local or Regional Government	Adaptation Action
Satellite Beach, FL	Collaboration with the Indian River Lagoon National Estuary Program led to the incorporation of sea level rise projections and policies into the city's comprehensive growth management plan (Gregg et al. 2011).
Portland, OR	Updated the city code to require on-site stormwater management for new development, and re-development and provides a downspout disconnection program to help promote onsite stormwater management (EPA 2010a) .
Lewes, DE	In partnership with Delaware Sea Grant, ICLEI-Local Governments for Sustainability, the University of Delaware, and state and regional partners, the City of Lewes undertook a stakeholder-driven process to understand how climate adaptation could be integrated into the hazard mitigation planning process. Recommendations for integration and operational changes were adopted by the City Council and are currently being implemented (City of Lewes 2011).
Groton, CT	Partnered with federal, state, regional, local, non-governmental, and academic partners through the EPA's Climate Ready Estuaries program to assess vulnerability to and devise solutions for sea level rise (Stults 2011).
San Diego Bay, CA	Five municipalities partnered with the port, the airport, and more than 30 organizations with direct interests in the future of the Bay to develop the San Diego Bay Sea Level Rise Adaptation Strategy. The strategy identified key vulnerabilities for the Bay and adaptation

	actions that can be taken by individual agencies, as well as through regional collaboration (Solecki and Rosenzweig 2012).
Chicago, IL	Through a number of development projects, the city has added 55 acres of permeable surfaces since 2008 and has more than four million square feet of green roofs planned or completed (City of Chicago 2008).
King County, WA	Created King County Flood Control District in 2007 to address increased impacts from flooding through activities such as maintaining and repairing levees and revetments, acquiring repetitive loss properties, and improving countywide flood warnings (Wolf 2009).
New York City, NY	Through a partnership with the Federal Emergency Management Agency (FEMA), the city is updating FEMA Flood Insurance Rate Maps based on more precise elevation data. The new maps will help stakeholders better understand their current and future flood risks and allow the city to more effectively plan for climate change (City of New York 2012).
Southeast Florida Climate Compact	Joint commitment among Broward, Miami-Dade, Palm Beach, and Monroe Counties to partner in reducing greenhouse gas emissions and adapting to climate impacts (Southeast Florida Compact Counties 2011).
Phoenix, AZ; Boston, MA; Philadelphia, PA; and New York, NY	Climate change impacts are being integrated into public health planning and implementation activities that include creating more community cooling centers, neighborhood watch programs, and reductions in the urban heat island effect (EPA 2011; Horton et al. 2012; White-Newsome et al. 2011).
Boulder, CO; New York, NY; and Seattle, WA	Water utilities in these communities are using climate information to assess vulnerability and inform decision-making (EPA 2010a).
City of Philadelphia	In 2006, the Philadelphia Water Department began a program to develop a green stormwater infrastructure, intended to convert more than one-third of the city's impervious land cover to "Greened Acres:" green facilities, green streets, green open spaces, green homes, etc., along with stream corridor restoration and preservation (ORNL 2012b).

There is no one-size-fits-all adaptation solution to the challenges of adapting to the impacts of climate change, as solutions will differ depending on context and scale as well as on local culture and internal capacity (National Climate Adaptation Summit Committee 2010; Solecki and Rosenzweig 2012).

5. Non-governmental and Private Sector

Many non-governmental entities have been significant actors in the national effort to prepare for climate change by providing assistance that includes planning guidance, implementation tools, contextualized climate information, best practice exchange, and help with bridging the science-policy divide to a wide-array of stakeholders (Agrawal 2008; Guston et al. 2000; Van Aalst et al. 2008). The Nature Conservancy, for example, established the Canyonlands Research Center in Monticello, Utah to facilitate research and develop conservation applications for resource issues under the multi-stresses of climate change and land-use demands in the Colorado Plateau region (Vose et al. 2012).

Table 28.4: Examples of Non-governmental Adaptation Efforts and Services

Types of Adaptation Efforts and Services	**Examples of Organizations Providing Services***
Adaptation planning assistance, including creation of guides, tools, and templates	Center for Climate Strategies, ICLEI-Local Governments for Sustainability, International Institute for Sustainable Development, The Nature Conservancy, World Resources Institute, World Wildlife Fund, Natural Resources Defense Council
Networking and best practice exchange	C40 Cities Climate Leadership Group, Adaptation Network, Center for Clean Air Policy, ICLEI-Local Governments for Sustainability, Institute for Sustainable Communities, Urban Sustainability Directors Network, World Business Council for Sustainable Development
Climate information providers	Union of Concerned Scientists, Urban Climate Change Research Network, Stockholm Environment Institute, U.S. Center
Policy, legal, and institutional support	Center for Climate and Energy Solutions (formerly Pew Center on Global Climate Change), Georgetown Climate Center
Aggregation of adaptation-pertinent information	Carbon Disclosure Project, Climate Adaptation Knowledge Exchange, Georgetown Climate Center

*This list contains examples of non-governmental organizations providing the identified services and should not be considered all-inclusive or a validation of actions claimed by the organizations.

With regard to the private sector, evidence from organizations such as the Carbon Disclosure Project (CDP) and the Securities and Exchange Commission's (SEC) Climate Change 10-K Disclosure indicate that a growing number of companies are beginning to actively address risks from climate change (CDP 2011). The World Business Council for Sustainable Development (WBCSD) and the Center for Climate and Energy Solutions (C2ES) have identified three types of risks driving private sector adaptation efforts, including risks to core operations, the value chain, and broader changes in the economy and infrastructure (PWC 2010; Sussman and Freed 2008; WBCSD 2009).

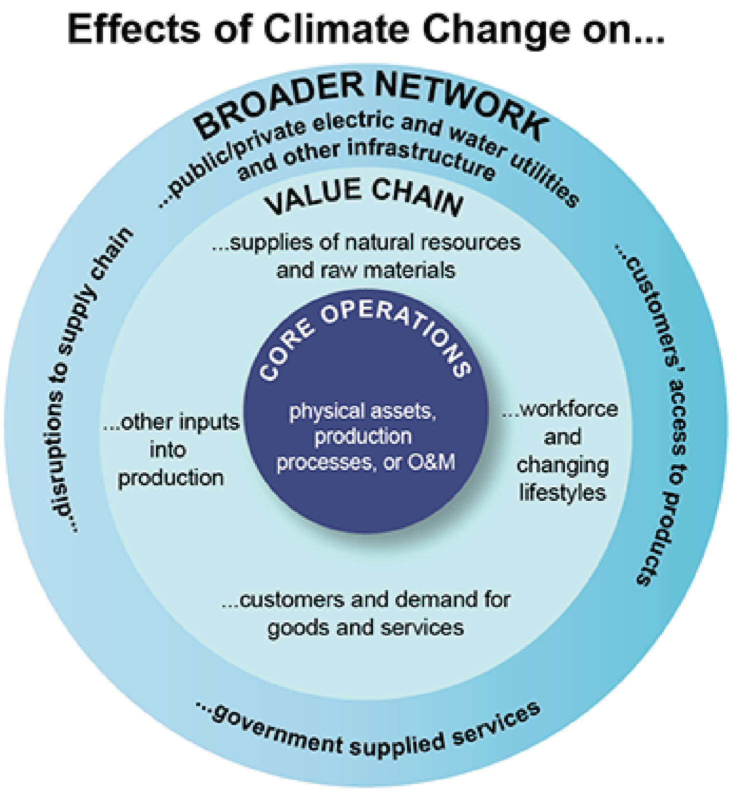


Figure 28.2. "Risk Disk" depicts three pathways by which risks posed by climate change can affect business, such as through core operations, value chain, and broader changes in the economy and infrastructure. (Sussman and Freed 2008).

This analysis is supported by responses to the 2011 CDP, and suggests that companies are concerned about how changes in the climate will impact issues such as feedstock, water supply and quality, infrastructure, core operations, supply chain, and customers' ability to use (and their need for) services (CDP 2011).

Table 28.5: Examples of Private Sector Actions to Adapt to Climate Risks Based on Responses to Carbon Disclosure Project

Company	Sector	Climate Risk	Examples of Actions Undertaken
Coca-Cola Company	Consumer Staples	Changes in physical climate parameters; Changes in other climate-related developments	Coca-Cola is working around the world to replenish the water used in finished beverages by participating in locally relevant water projects that support communities and nature. Since 2005, the Coca-Cola system has engaged in more than 320 projects in 86 countries. The range of community projects includes watershed protection; expanding community drinking water and sanitation access; water for productive use, such as agricultural water efficiency; and education and awareness programs. (http://www.thecoca-colacompany.com/citizenship/conservation_partnership.html)
ConAgra Foods, Inc.	Consumer Staples	Company experienced weather-related sourcing challenges, such as delayed tomato harvesting due to unseasonably cool weather, and difficulty sourcing other vegetables due to above normal precipitation.	As part of its business continuity planning, ConAgra Foods has analyzed its supply risk to develop strategic partnerships with suppliers, minimize sole-sourced ingredients, and identify alternate suppliers and contract manufacturers to minimize production disruptions in the instance of an unexpected disruption in supply. (http://company.conagrafoods.com/phoenix.zhtml?c=202310&p=Policies_Environment)
Constellation Brands	Consumer Staples	Changes in physical climate parameters; Changes in other climate-related developments	Constellation has already taken adaptation actions, particularly in California where water availability is an issue, to manage or adapt to these risks. Constellation is working with numerous organizations to help fund industry-based research to determine potential climate change impacts on vineyard production.
Munich Re	Reinsurance	Changes in regulation; Changes in physical climate parameters; Changes in other climate-related developments	Since 2007, a Group-wide climate change Strategy covering all aspects of climate change – e.g. weather-related impact, regulatory impact, litigation and health risks, etc. – has supported their core Corporate Strategy. The Strategy is based on five pillars: mitigation, adaptation, research, in-house carbon dioxide (CO_2) reduction, and advocacy. (http://www.munichre.com/en/group/focus/climate_change/default.aspx)
Pacific Gas and Electric Company (PG&E)	Utilities	Changes in regulation; changes in physical climate parameters; Changes in other climate-related developments	PG&E's adaptation strategies for potential increased electricity demand include expanded customer energy efficiency and demand response programs and improvements to its electric grid. PG&E is proactively tracking and evaluating the potential impacts of reductions to Sierra Nevada snowpack on its hydroelectric system, and has developed adaptation strategies to minimize them. Strategies include maintaining higher winter carryover reservoir storage levels, reducing conveyance flows in canals and flumes in response to an increased portion of precipitation falling as rain, and reducing discretionary reservoir water releases during the late spring and summer. PG&E is also working with both the US Geological Survey (USGS) and the California Department of Water Resources to begin using the USGS Precipitation-Runoff Modeling System (PRMS) watershed model, to help manage reservoirs on watersheds experiencing mountain snowpack loss. (http://www.pge.com/about/environment/commitment/)
SC Johnson & Son, Inc.	Household Products	Changes in physical climate parameters	SC Johnson is adjusting to the various physical risks that climate change imposes through a diversified supplier and global manufacturing base. In March 2009, SC Johnson announced a broad ingredient communication program. SC Johnson assesses risks along each ingredient's supply chain to ensure that the company is sourcing from a geographically diverse supplier base. In addition to evaluating product ingredients, SC Johnson has also diversified its operations around the world, allowing it to maintain business continuity in the face of a regional climate-related disruption.

			(http://www.scjohnson.com/en/commitment/overview.aspx)
Spectra Energy, Inc.	Energy	Changes in regulation; Changes in physical climate parameters; Changes in other climate-related developments	Spectra Energy uses a corporate-wide risk analysis framework to ensure the oversight and management of its four major risk categories: financial, strategic, operational, and legal risks. Physical risks posed by climate change fall within these categories and the company uses risk management committees to ensure that all material risks are identified, evaluated and managed prior to financial approvals of major projects. (http://www.spectraenergy.com/Sustainability/)

Some companies are taking action to not only avoid risk, but to explore potential opportunities embodied in a changing climate, such as developing new products and services; developing or expanding existing consulting services; expanding into new operational territories; extending growing seasons and hours of operation; and responding to increased demand for existing products and services (Agrawala et al. 2011; CDP 2011; Dell and Pasteris 2010; Oxfam America 2009; PWC 2010).

I. Adaptation Process

General patterns in adaptation processes are only beginning to emerge, with similarities discernible across sectors, systems, and scales (Anguelovski and Carmin 2011; Dell and Pasteris 2010; Means et al. 2010).

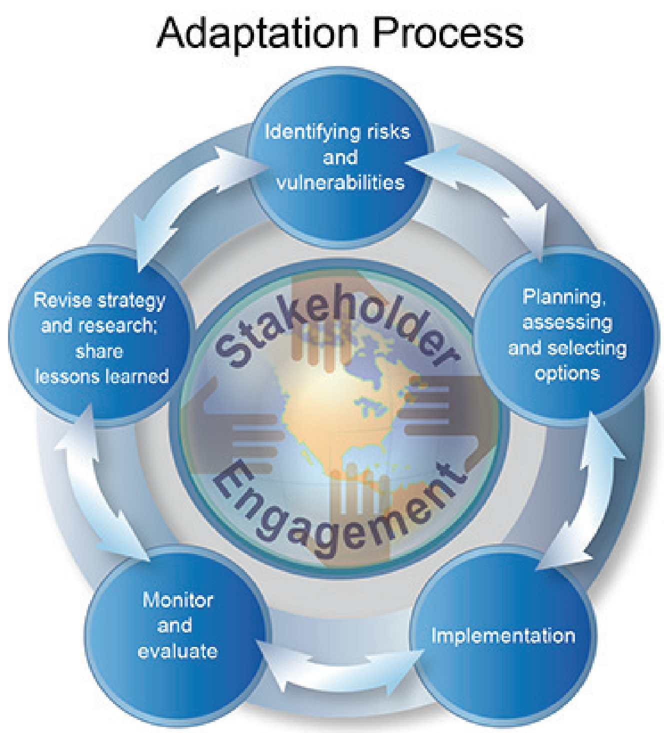


Figure 28.3: Generalized Adaptation Process adapted from America's Climate Choices

This is not a step-wise or linear process; various stages can be occurring simultaneously, in a different order, or be omitted completely.

Identifying and Understanding Risk, Vulnerabilities, and Opportunities

Most adaptation action is currently in the initial phase, with many actors focusing on identifying the relevant climate risks and conducting current and future risk and vulnerability assessments of their assets and resources (Carmin et al. 2012; Glick et al. 2011; Ingram et al. 2012; Lackstrom et al. 2012; NRC 2010a; Rowland et al. 2011; USGS 2012b; West et al. 2009). In 2011, only 13% of 298 U.S. municipalities surveyed, had completed vulnerability or risk assessments – but 42% expected to complete an assessment in the future (Carmin et al. 2012). At least 21 state fish and wildlife agencies have undertaken climate vulnerability assessments or recently completed an assessment of a particular species, habitat, or both (AFWA 2011). Multiple qualitative and quantitative methods are used to understand climate vulnerability and risk, including case studies and analogue analyses, scenario analyses, sensitivity analyses, monitoring of key species, and peer information sharing (Barrett et al. 2011; EPA 2011; Ford et al. 2010; Füssel 2007a; Heller and Zavaleta 2009; Hulme and Dessai 2008; NPS 2010; Pahl-Wostl et al. 2011; USGS 2012b).

Planning, Assessing, and Selecting Options

Once risks and vulnerabilities are understood, the next stage typically involves identifying, evaluating, and selecting options for response to existing and future changes in the climate (NPS 2010). Decision-support planning methods and associated tools help to identify flexible and context-relevant adaptation activities for implementation (Means et al. 2010; NRC 2010a). Participatory approaches support the integration of stakeholder perspectives and context-specific information into decision-making (Fazey et al. 2009; Few et al. 2007; Preston et al. 2011; Smit and Wandel 2006), often by having community members and governing institutions work collectively to define the problem and design adaptation strategies that are robust while being sensitive to stakeholder values (Brunner 2005; Preston et al. 2011; Stern et al. 1996; World Bank 2008). Moreover, regional collaboration has emerged as an effective strategy for defining common approaches to reducing potential threats, selecting metrics for tracking purposes, and creating governance structures to help navigate political challenges (ICLEI 2012; Moser and Ekstrom 2010b; Pyke 2011; Southeast Florida Compact Counties 2011).

Common approaches to adaptation planning include “mainstreaming” or integrating climate adaptation into existing management plans (for example, hazard mitigation, ecosystem conservation, water management, public health, risk contingency, and energy) or developing stand-alone adaptation plans (ASTHO 2012; Culver et al. 2012; Horton et al. 2012; Lackstrom et al. 2012).

Many frameworks, tools, and approaches have emerged to help decision makers make decisions in light of uncertainty (Kareiva 2008; Means et al. 2010). Many of these, however, are specific to particular localities or resources, are not easy to use, and require sophisticated knowledge of climate change (Federspiel 2012; Hammill and Tanner 2011). In general, these approaches promote options that allow reversibility, preserve future options, can tolerate a variety of impacts, and are flexible, such that mid-course adjustments are possible (OTA 1993; Wilby and Vaughan 2011). Among these approaches are Robust Decision Making (RDM), Iterative Risk Management (IRM), Adaptive Management or Co-Management, Portfolio Management, and Scenario Planning (Gregg et al. 2011; Groves and Lempert 2007; Kareiva 2008; Lempert et al. 2006; Moore et al. 2012; Moser 2012; NPS 2010; NRC 2004, 2010a; Williams 2012) (see Ch. 26: Decision Support for more on decision frameworks, processes, and tools).

Implementation

Because climate change adaptation action in the United States is relatively new, there is little peer-reviewed literature on adaptation actions, or evaluations of their successes and failures (Ford et al. 2011; Ingram et al. 2012; Moser 2009; NRC 2010a). Many of the documents submitted as part of the 2013 National Climate Assessment (NCA) process indicate that adaptation actions are being implemented for a variety of reasons – often with an aim toward reducing current vulnerabilities to hazards or extreme weather events, such as forest thinning and fuel treatments that reduce fire hazards in national forests or through the diversification of supply chain sourcing in the private sector (CDP 2011; Vose et al. 2012). Additionally, an increasing movement toward mainstreaming climate adaptation concerns into existing processes means that discerning unique climate adaptation activities will be a challenge (Dovers and Hezri 2010; Lackstrom et al. 2012).

Monitoring and Evaluation

There is little literature evaluating the effectiveness of adaptation actions (Means et al. 2010; Preston et al. 2011; Solecki and Rosenzweig 2012; Vose et al. 2012). Evaluation and monitoring efforts, to date, have focused on the creation of process-based rather than outcome-based indicators (Culver et al. 2012; Preston et al. 2011). A number of efforts are underway to create indicators related to climate adaptation (USGCRP 2012), including work by the National Climate Assessment Development Advisory Committee Indicators Working Group (Janetos et al. 2012) and the U.S. Environmental Protection Agency (EPA 2010b).

Revise Strategies/Processes and Information Sharing

Uncertainty about the future climate as well as about population growth, economic development, response strategies, and other social and demographic issues, can stymie climate adaptation activity (McCollum et al. 2011; Moore et al. 2012; USGS 2012b). Through iterative processes, however, stakeholders can regularly evaluate the appropriateness of planned and implemented activities and revise them as new information becomes available (EPA 2011; NPS 2010; NRC 2010a). Additionally, the sharing of best practices and lessons learned can be pivotal means to advancing understanding and uptake of climate adaptation activity (Lackstrom et al. 2012; Preston et al. 2011). The use of established information-sharing networks such as regional climate initiatives are illustrations of the types of networks that have supported stakeholder adaptation activity to-date (Means et al. 2010; Preston et al. 2011; Solecki and Rosenzweig 2012; WBCSD 2009).

II. Climate Adaptation Map

This map highlights some climate adaptation activities taking place in different geographical regions and scales in the United States. It is not intended to be a comprehensive compilation of national adaptation activity.

Table 28.6 --- which will be turned into Figure 28.4: Global Adaptation Map

	Adaptation Activity
1.	The State of Hawaii Office of Planning, in cooperation with university, private, state, and federal scientists and others, has drafted a framework for climate change adaptation that identifies sectors affected by climate change, and outlines a process for coordinated statewide adaptation planning. (Adapting to Climate Change: A Planning Guide for State Coastal Managers, (NOAA 2010)
2.	One of the priorities of the Hawaii State Plan is preserving water sources through conservation of the forests, as indicated in their "Rain Follows The Forest" report. (http://hawaii.gov/dlnr/chair/pio/nr/2011/The-Rain-Follows-the-Forest.pdf)
3.	New England Federal Partners is a multi-agency group formed to support the needs of the states, tribes, and communities of the New England Region and to facilitate and enable informed decision-making on issues pertaining to coastal and marine spatial planning, climate mitigation, and climate adaptation throughout the region. (http://www.epa.gov/region1/eco/energy/adaptation-efforts-epane.html)
4.	The City of Philadelphia is greening their combined sewer infrastructure to protect rivers, reduce greenhouse gas emissions, improve air quality, and enhance adaptation to a changing climate (http://www.phillywatersheds.org/ltcpu/)
5.	The City of Keene, NH, replaced culverts with larger ones that were designed to withstand projected increases in precipitation and population demand. (City of Keene 2010)
6.	New York City has created a Green Infrastructure Plan and is committed to goals that include the construction of enough green infrastructure throughout the city to manage 10% of the runoff from impervious surfaces by 2030. (http://www.nyc.gov/html/dep/html/stormwater/nyc_green_infrastructure_plan.shtml)
7.	The City of Lewes, DE, undertook an intensive stakeholder process to integrate climate change into the city's updated hazard mitigation plan. (http://www.ci.lewes.de.us/Hazard-Mitigation-Climate-Adaptation-Action-Plan/)
8.	Local governments and tribes throughout Alaska, such as those in Homer, are planting native vegetation and changing the coastal surface, moving inland or away from rivers, and building riprap walls, groins, or seawalls. (http://www.cakex.org/virtual-library/2555)
9.	Villages are physically being relocated because of climate impacts such as sea level rise and erosion; these include Newtok, Shishmaref, Kivalina, and dozens of other villages. (http://www.commerce.state.ak.us/dca/planning/npg/Newtok_Planning_Group.htm)

10. The City of Cedar Falls recently passed legislation that includes a new floodplain ordinance that expands zoning restrictions from the 100-year floodplain to the 500-year floodplain, because this expanded floodplain zone better reflects the flood risks experienced by the city during the 2008 floods. (http://www.epa.gov/dced/pdf/iowa_climate_adaptation_report.pdf)

11. In January 2011, the Michigan Department of Community Health (MDCH) released the *Michigan Climate and Health Adaptation Plan*, which has a goal of "preparing the Public Health System in Michigan to address the public health consequences of climate change in a coordinated manner." In September 2010, MDCH received three years' funding to implement this plan as part of the Climate-Ready States and Cities Initiative of CDC. (http://www.michigan.gov/documents/mdch/MDCH_climate_change_strategicPlan_final_1-24-2011__343856_7.pdf)

12. The City of Chicago was one of the first cities to officially integrate climate adaptation into a citywide Climate Adaptation Plan. Since its release, a number of strategies have been implemented to help the city manage heat, protect forests, and enhance green design, such as their work on green roofs. (http://www.chicagoclimateaction.org/pages/adaptation/11.php)

13. The City of Grand Rapids, MI, recently released a Sustainability Plan that integrates future climate projections to ensure that the economic, environmental, and social strategies embraced are appropriate for today as well as the future. (http://grcity.us/enterprise-services/officeofenergyandsustainability/Pages/default.aspx/)

14. Tulsa, OK, has a three-pronged approach to reducing flooding and managing stormwater: 1) prevent new problems by looking ahead and avoiding future downstream problems from new development (for example, requiring on-site stormwater detention); 2) correct existing problems and learn from disasters to reduce future disasters (for example, through watershed management and the acquisition and relocation of buildings in flood-prone areas); and 3) act to enhance the safety, environment, and quality of life of the community through public awareness, an increase in stormwater quality, and emergency management. (http://www.smartcommunities.ncat.org/articles/rooftop/program.shtml)

15. Firewise Communities USA is a nationwide program of the National Fire Protection Association and is co-sponsored by USDA Forest Service, DOI, and the National Association of State Foresters. According to the Texas Forest Service, there are more than 20 recognized Texas Firewise Communities. The Texas Forest Service works closely with communities to help them to reach Firewise Community status and offers a variety of awareness, educational, informational, and capacity-building efforts, such as *Texas Wildscapes*, a program that assists in choosing less fire-friendly plants. (http://texasforestservice.tamu.edu/main/article.aspx?id=1602)

16. After the heavy rainfall events of 2004 that resulted in significant erosion on his farms, Dan Gillespie, a farmer with NRCS in Norfolk, NE, began experimenting with adding cover crops to the no-till process. It worked so well in reducing erosion and increasing crop yields that he is now sharing his experience with other farmers (http://www.lenrd.org/projects-programs/; http://www.notill.org/; personal communication, L Carter, June 1, 2012)

17. Point Reyes National Seashore is preparing for climate change by removing two dams that are barriers to water flow and fish migration. This change restores ecological continuity for anadromous fish (those that migrate from the sea to fresh water to spawn), creating a more resilient ecosystem. (http://www.cakex.org/case-studies/1083)

18. Western Adaptation Alliance is a group of 10 cities in four states in the Intermountain West that share lessons learned in adaptation planning, develop strategic thinking that can be applied to specific community plans, and join together to generate funds to support capacity building, adaptation planning, and vulnerability assessment. (http://sustainablecommunitiesleadershipacademy.org/workshops/regional-western-adaptation-alliance)

19. Navajo Nation used information on likely changes in future climate to help inform their drought contingency plan. (Navajo Nation Department of Water Resources 2003)

20. California Department of Health and the Natural Resources Defense Council collaborated to create the *Public Health Impacts of Climate Change in California: Community Vulnerability Assessment and Adaptation Strategies* report, which is being used to inform public health preparedness activities in the State. (http://www.ehib.org/papers/Heat_Vulnerability_2007.pdf) (English 2007)

21. State of Idaho successfully integrated climate adaptation into the State's Wildlife Management Plan. (USGS 2012b) (**http://fishandgame.idaho.gov/public/wildlife/cwcs/**)

22. The Rising Tides Competition was held in 2009 by the San Francisco Bay Conservation and Development Commission to elicit ideas for how the Bay could respond to sea level rise. (http://www.risingtidescompetition.com/risingtides/Home.html)

23. The City of Flagstaff, Arizona, created a resilience strategy and passed a resilience policy, as opposed to a formal adaptation plan, as a means to institutionalize adaptation efforts in city government operations (City of Flagstaff, 2012).

24. The Olympic National Forest and Olympic National Park were sites of case studies looking at how to adapt management of federal lands to climate change. Sensitivity assessments, review of management activities and constraints, and adaptation workshops in the areas of hydrology and roads, fish, vegetation, and wildlife were all components of the case study process. (http://www.fs.fed.us/pnw/pubs/pnw_gtr844.pdf)

25. King County Flood Control District was reformed to merge multiple flood management zones into a single county entity for funding and policy oversight for projects and programs – partly in anticipation of increased stormwater flows due to climate change. (http://www.nerrs.noaa.gov/doc/pdf/training/strategies_king_county.pdf)

26. The Water Utilities Climate Alliance has been working with member water utilities to ensure that future weather and climate considerations are integrated into short- and long-term water management planning. (Culver et al. 2012) (http://www.wucaonline.org/html/)

27. Seattle's RainWatch program uses an early warning precipitation forecasting tool to help inform decisions about issues such as drainage operations. (CEQ, 2011a) (http://www.atmos.washington.edu/SPU/)

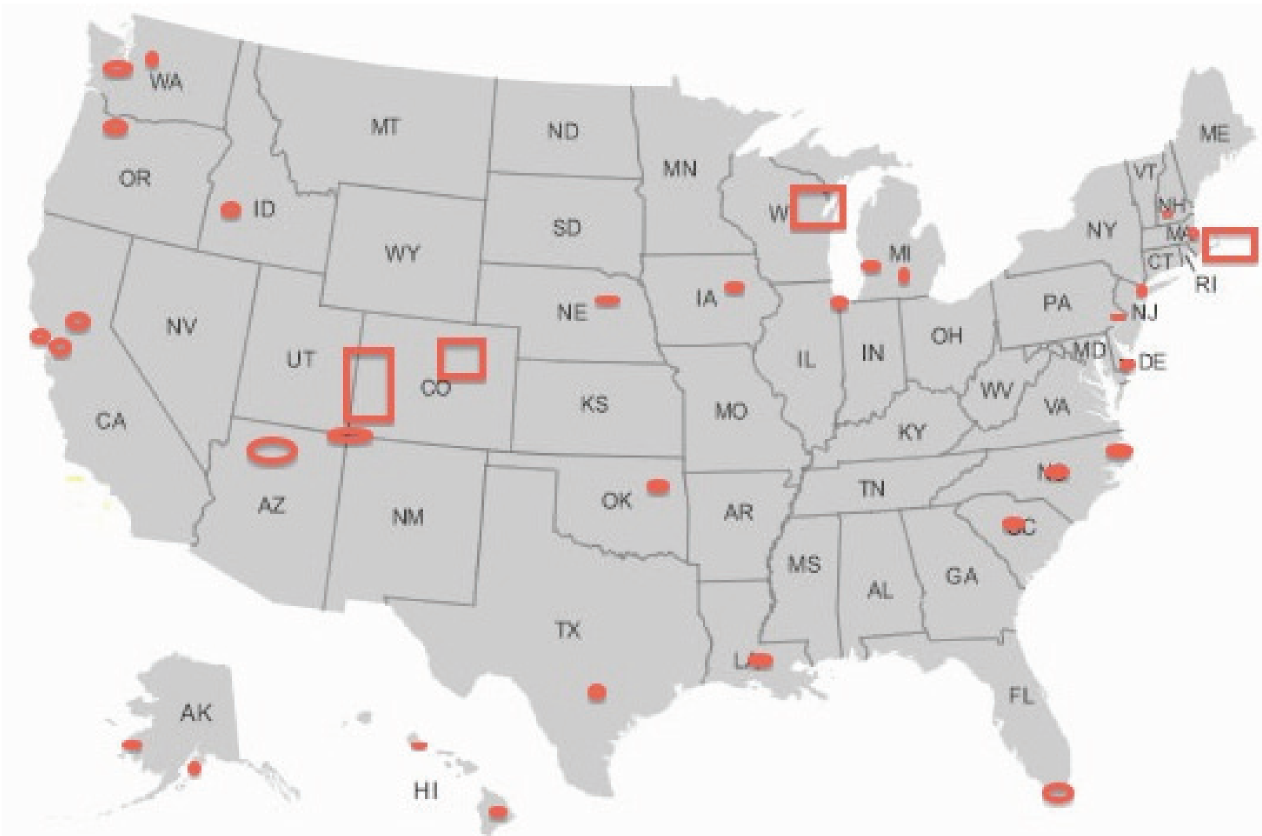
28. City of Portland and Multnomah County created a Climate Action Plan that includes indicators to help them gauge progress in planning and implementing adaptation actions. (City of Portland 2009) ((http://www.portlandoregon.gov/bps/article/268612)

29. In 2010, the State of Louisiana launched a $10 million program to assist communities that had been impacted by Hurricanes Gustav and Ike in becoming more resilient to future environmental problems. Twenty-nine communities from around the State were awarded resiliency development funds. The Coastal Sustainability Studio at Louisiana State University started working in 2012 with all 29 funded communities, as well as many that did not receive funds, to develop peer-learning networks, develop best practices, build capacity to implement plans, and develop planning tools and a user-inspired and useful website to increase community resiliency in the State. (http://lra.louisiana.gov/index.cfm?md=newsroom&tmp=detail&articleID=608 and http://resiliency.lsu.edu/)

30. FWS and The Nature Conservancy are cooperating in a pilot adaptation project to address erosion and salt water intrusion, among other issues, in the Alligator River Refuge. This project incorporates multiple agencies, native knowledge, community involvement, local economics, and technical precision. (http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/northcarolina/afield-spring-2011.pdf)

31. North and South Carolina are actively working to revise their state wildlife strategies to include climate adaptation (Lackstrom et al. 2012).

32. The Southeast Florida Climate Compact is a collaboration of the four southernmost counties in Florida (Monroe, Broward, Palm Springs, and Miami-Dade) focusing on enhancing regional resilience to climate change and reducing regional greenhouse gas emissions (Southeast Florida Compact Counties 2011). (http://www.southeastfloridaclimatecompact.org/documents/DraftRCAP.pdf)



III. Barriers to Adaptation

Despite emerging recognition of the necessity of climate change adaptation, many barriers still impede efforts to build local, regional, and national-level resilience. Barriers are obstacles that can delay, divert, or temporarily block the adaptation process (Ekstrom et al. 2011) and include: difficulties in using climate change projections for decision-making; lack of resources to begin and sustain adaptation efforts; fragmentation of decision-making; institutional constraints; lack of leadership; and divergent risk perceptions/cultures and values (Bierbaum et al. 2013 ; NRC 2010a). Barriers are distinguished from physical or ecological limits to adaptation, such as physiological tolerance of species to changing climatic conditions that cannot be overcome (except with technology or some other physical intervention) (Adger et al. 2007; Gregg et al. 2011; McIlgorm et al. 2010; USGS 2012b).

Table 28.7: Summary of Adaptation Barriers

Barrier	Specific Examples	References
Climate Change Information and Decision-Making	• Uncertainty about future climate impacts • Disconnect between information providers and information users • Fragmented, complex, and often confusing information • Lack of climate education for professionals and the public • Lack of usability and accessibility of existing information	(Barsugli et al. 2012; Brunner 2012; Carmin et al. 2012; Culver et al. 2012; Dilling and Lemos 2011; Fowler and Wilby 2007; Groves and Lempert 2007; Hauser and Jadin 2012; Horton et al. 2012; Kareiva 2008; Kerr 2011; Lackstrom et al. 2012; Larsen 2011; Lebow 2012; Marra 2012; McCollum et al. 2011; McNie 2007; Mitchell 2010; National Climate Adaptation Summit Committee 2010; Needham et al. 2012; NRC 2007, 2010a; OTA 1993; Schramm 2012; USGS 2012b; Vose et al. 2012; White-Newsome et al. 2011; Winkler 2012)
Lack of Resources to Begin and Sustain Adaptation Efforts	• Lack of financial resources / no dedicated funding • Limited staffing capacity • Underinvestment in human dimensions research	(Brugger and Crimmins 2011; Brunner 2012; Carmin et al. 2012; Garfin et al. 2012; Gregg et al. 2011; Ingram et al. 2012; Lackstrom et al. 2012; Marra 2012; Mittal 2009; Needham et al. 2012; Schramm 2012; Simmonds 2011; USGS 2012b)
Fragmentation of Decision-Making	• Lack of coordination within and across agencies, private companies, and non-governmental organizations • Uncoordinated and fragmented research efforts • Disjointed climate related information • Fragmented ecosystem and jurisdictional boundaries	(Clark and Levin 2010; Horton et al. 2012; Lebow 2012; National Climate Adaptation Summit Committee 2010; NRC 2009; OTA 1993; Simmonds 2011; USGS 2012b; Winkler 2012)
Institutional Constraints	• Lack of institutional flexibility • Rigid laws and regulations • No legal mandate to act • Use of historical data to inform future decisions • Restrictive management procedures • Lack of operational control or influence	(Adger et al. 2009; Brugger and Crimmins 2011; Carpenter and Brock 2008; Craig 2008; Folke 2006; Garfin et al. 2012; Gregg et al. 2011; Lee 1994; Marra 2012; McNeeley 2012; Moser and Ekstrom 2012; Nelson et al. 2007; NRC 2004; Simmonds 2011; USGS 2012b)
Lack of Leadership	• Lack of political leadership • Rigid and entrenched political structures • Polarization	(Brugger and Crimmins 2011; Ding et al. 2011; Leiserowitz et al. 2011a; Moser 2012; Moser and Ekstrom 2012; Schramm 2012; Smith et al. 2009; Smith et al. 2010)
Divergent Risk Perceptions, Cultures, and Values	• Conflicting values/risk perceptions • Little integration of local knowledge, context, and needs with traditional scientific information • Cultural taboos and conflict with cultural beliefs • Resistance to change due to issues such as risk perception	(Adger et al. 2009; Ding et al. 2011; Doria et al. 2009; Gifford 2011; Kahan et al. 2007; Kahan et al. 2011; Lackstrom et al. 2012; Leiserowitz 2006; McNeeley 2012; NRC 2009; Renn 2011; Renn et al. 2011; Simmonds 2011; Van Aalst et al. 2008; Verweij et al. 2006; Weber and Stern 2011)

IV. Overcoming Barriers to Success

Individuals within and across sectors and regions are organizing to collectively overcome barriers and adapt to climate change. Colorado River Basin water resource managers, government leaders, federal agencies, universities, non-governmental organizations (NGOs), and the private sector are collaborating on strategies for managing water under a changing climate through partnerships like the Western Governors Association (WGA) and WestFAST (Western Federal Agency Support Team).

In Wisconsin, the Northern Institute of Applied Climate Science and the U.S. Forest Service, working with multiple partners, initiated a “Climate Change Response Framework” integrating climate-impacts science with forest management. In Cape Cod, Massachusetts, the U.S. Department of Transportation’s Volpe Center worked with federal, regional, state, and local stakeholders to integrate climate change mitigation and adaptation considerations into existing and future transportation, land-use, coastal, and hazard-mitigation processes.

Through the creation of the National Integrated Drought Information System (NIDIS), the federal government, in partnership with the National Drought Mitigation Center (NDMC), states, tribes, universities, and others, has improved capacity to proactively manage and respond to drought-related risks and impacts through: 1) the provision of drought early warning information systems with local/regional input on extent, onset, and severity; 2) a web-based drought portal featuring the U.S. Drought Monitor and other visualization tools; 3) coordination of research in support and use of these systems; and 4) leveraging of existing partnerships, forecasting, and assessment programs.

V. Next Steps

Adaptation to climate change is in a nascent stage. The federal government is beginning to develop the institutions and practices necessary to address adaptation, including through efforts such as regional climate centers within the U.S. Department of Agriculture, the National Oceanic and Atmospheric Administration (a division of the Department of Commerce), and the Department of the Interior. A number of states and local governments are engaging in adaptation planning, but most have not taken action to implement the plans (Bierbaum et al. 2013). Despite some early successes, the pace and extent of adaptation activities are not proportional to the risks to people, property, infrastructure, and ecosystems from climate change; important opportunities are also being overlooked.

One of the key areas of focus for global change research is enabling research and development to advance adaptation across scales, sectors, and disciplines. This includes research for overcoming the barriers identified in Section III, such as strategies that foster coordination, better communication, and knowledge sharing amongst fragmented governing structures and stakeholders. Research on the kinds of information users desire and how to deliver that information in contextually appropriate ways, as well as research on decision-making in light of uncertainty about climate change and other considerations, will be equally important.

In addition to these areas, emerging areas of needed research include:

- *Costs and Benefits of Adaptation.* Methodologies to evaluate the relevant costs of adaptation options, as well as the costs of inaction, need to be developed.
- *A Compendium of Adaptation Practices*. A central and streamlined database of adaptation options implemented at different spatial and temporal scales is needed. Information on the adaptation actions, how effective they were, what they cost, and how monitoring and evaluation were conducted should be part of the aggregated information. (National Climate Adaptation Summit Committee 2010; NRC 2010a).
- *Adaptation and Mitigation Interactions*. Research and analysis on the growing and competing demands for land, water, and energy and how mitigation actions could affect adaptation options, and vice versa (Bloetscher et al. 2011; Ingram et al. 2012; ORNL 2012a; Skaggs et al. 2012).
- *Critical Adaptation Thresholds*. Research to identify critical thresholds beyond which social and/or ecological systems are unable to adapt to climate change. This should include analyzing historical and geological records to develop models of "breakpoints" (NAST 2000; National Climate Adaptation Summit Committee 2010).
- *Adaptation to Extreme Events*: Research on preparedness and response to extreme events such as droughts, floods, intense storms, and heatwaves in order to protect people, ecosystems, and infrastructure. Increased attention must be paid to how extreme events and variability may change as climate change proceeds and how that affects adaptation actions (IPCC 2012; Kates et al. 2012).

A key federal role in adaptation, as indicated in the literature, has been the role of enabling and facilitating adaptation within states, regions, local communities, and the public and private sectors (NRC 2010a). The approaches include working to limit current institutional constraints to effective adaptation, funding pilot projects, providing useful and usable adaptation information – including disseminating best practices, and helping develop tools and techniques to evaluate successful adaptation. Some companies in the private sector and numerous non-governmental organizations have also taken action, particularly in capitalizing on the opportunities associated with facilitating adaptive actions and building tools and technologies that are useful in enhancing resilience. Actions and collaborations have occurred across all scales. At the same time, barriers to effective implementation continue to exist.

Effective adaptation will require ongoing, flexible, transparent, inclusive, and iterative decision-making processes, collaboration across scales of government and sectors, and the continual exchange of best practices and lessons learned. All stakeholders have a critical role to play in ensuring the preparedness of our society to extreme events and long-term changes in climate.

VI. Case Studies

Illustrative Case One: National Integrated Drought Information System

NIDIS (National Integrated Drought Information System), originally proposed by the WGA and established by Congress in 2006 (Hayes and Pulwarty 2012), is a federally-created entity that improves the nation's capacity to proactively manage drought-related risks across sectors, regions, and jurisdictions. It was created by Congress to "enable the Nation to move from a reactive to a more proactive approach to managing drought risks and impacts." NIDIS has successfully brought together government partners and research organizations to advance a warning system for drought-sensitive areas.

The creation of NIDIS involved many years of development and coordination among federal, state, local, regional, and tribal partners with the help of Governors' associations and Senate and congressional leaders. NIDIS provides: 1) drought early warning information systems with regional detail concerning onset and severity; 2) a web-based portal (www.drought.gov); 3) coordination of federal research in support of and use of these systems; and 4) leveraging of existing partnerships and of forecasting and assessment programs. NIDIS currently supports work on water supply and demand, wildfire risk assessment and management, and agriculture. Regional drought early warning system pilot projects have been established to illustrate the benefits of improved knowledge management, improved use of existing and new information products, and coordination and capacity development for early warning systems. These prototype systems are in the Upper Colorado Basin, the Apalachicola-Chattahoochee-Flint River Basin in the Southeast, the Four Corners region in the Southwest, and the State of California. The NIDIS Outlook in the Upper Colorado Basin provides early warning information every week, for example, that is utilized by a variety of users from Federal agencies, water resource management, and the recreation industry.

The Western Governors Association, the U.S. Congress, and others have formally acknowledged that NIDIS provides a successful example of achieving effective federal-state partnerships by engaging both leadership and the public, and establishing an authoritative basis for integrating monitoring and research to support risk management. Some of NIDIS' keys to success include:

- **Useable Technology and Information for Decision Support:** The production of the U.S. Drought Monitor map which integrates multiple indicators and indices from many data sources, was developed before NIDIS was established and has become a useful visual decision support tool for monitoring and characterizing drought onset, severity, and persistence. NIDIS has engaged regional and local experts in refining the regional details of this national product and in "ground truthing" maps via email discussions and webinars.

- **Financial Assistance:** Federal funding was allocated to NOAA specifically for NIDIS, but leveraged in kind by other agencies and partners.

- **Institutional/Partnerships:** Effective collaborations, partnerships, and coordination with NOAA, WGA, USDA, DOI, and USGS as well as local, regional, state, and tribal partners and with the National Drought Mitigation Center at the University of Nebraska, Lincoln, have led to multi-institutional "buy-in".

- **Institutional/Policy:** The NIDIS Act was oriented toward the improvement of coordination across federal agencies and with regional organizations, universities, and states. It focused on the application of technology, including the Internet, and on impact assessments for decision support. A key aspect of NIDIS is the development of ongoing regional outlook forum based on the above information to build awareness of the drought hazard and to embed information in planning and practice (in partnership with the National Drought Mitigation Center, the Regional Integrated Sciences and Assessments (RISA), and other research-based boundary organizations) to reduce risks and impacts associated with drought.

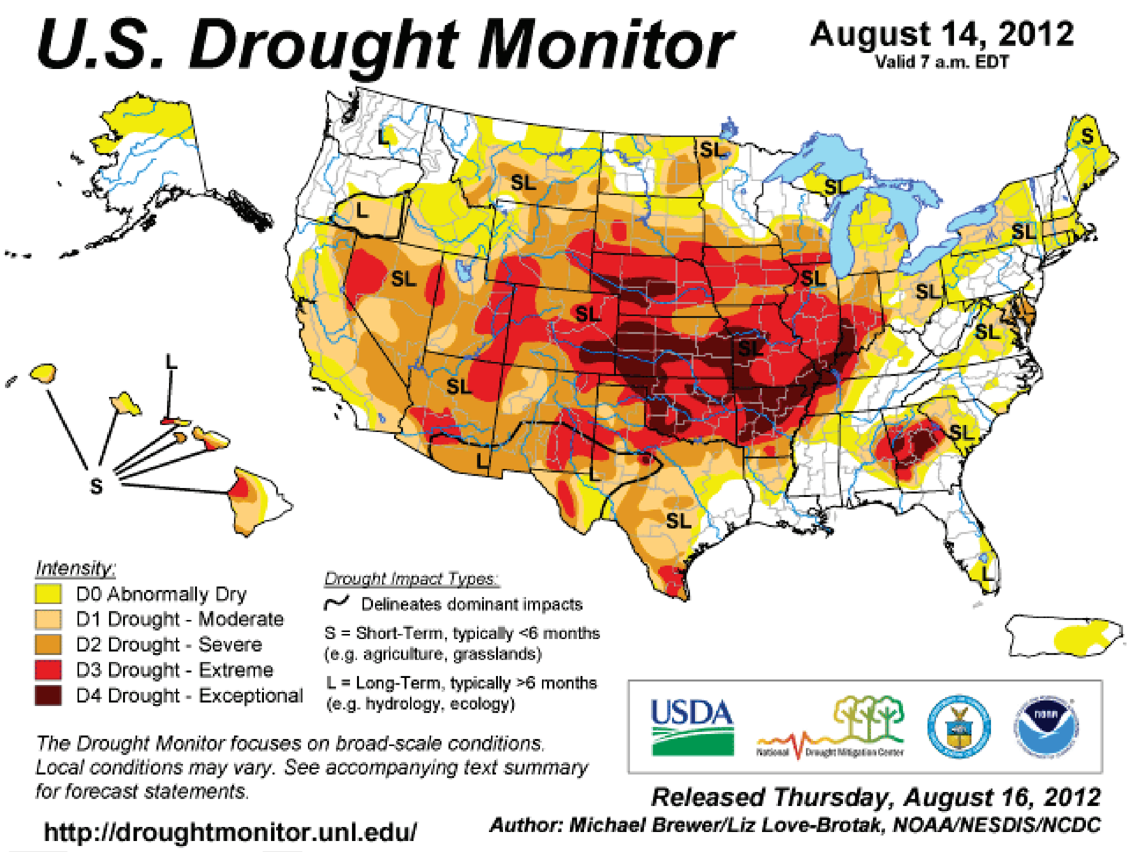


Figure 28.5: U.S. Drought Monitor Map accessed on August 20, 2012. The U.S. Drought Monitor is produced in partnership between the national Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC-UNL.

- **Leadership and Champions:** NIDIS supporters worked at all levels over more than two decades (1990s and 2000s) to establish the NIDIS Act, including political (WGA, Southern Governors Association, National Governors Association, U.S. Senators, and congressmen); scientific (Wilhite, Pulwarty, Verdin); and federal agencies (NOAA, USDA, DOI).

- **Risk Perceptions:** Whereas drought had been considered primarily a western issue in previous decades, drought is now regularly impacting the south, southeast, and northeast parts of the country and response strategies are needed. Because of the 2012 drought, more than 63% of the contiguous U.S. by the end of July was classified as experiencing moderate to exceptional drought and more than 3,200 heat records were broken in June 2012 alone (NOAA 2012; Schwalm et al. 2012)

Illustrative Case Two: Adaptive Governance in the Colorado River Basin
The Colorado River supplies water and valuable ecosystem services to 33 million people and is vulnerable to climate change because of decreases in mountain snowpack and water availability, increased competition among water users, fires, drought, invasive species, and extended extreme heat events, among other threats (Cayan et al. 2010; Christensen and Lettenmaier 2007; Garfin et al. 2012; Hidalgo et al. 2009; Pierce et al. 2008; Seager and Vecchi 2010). The 1922 Colorado River Compact, which allocates water among seven U.S. states and Mexico, was agreed upon in a particularly wet time period (Gray et al. 2011; Woodhouse et al. 2006); thus the river water is already over-allocated for current conditions. Given the likelihood of having less water because of climate change, resource managers and government leaders are increasingly recognizing that water must be managed with flexibility to respond to the projected impacts and the range of possible future climates (Brown 2010; Garfin et al. 2012). Multiple actors across all scales of governance (including tribal, local, state, and federal), non-governmental organizations, and the private sector are organizing and working together to address these concerns and the relationship between climate and other stresses in the basin.

The Western Governors' Association (WGA) spearheaded adaptation efforts to enable federal, state, tribal, local, and private sector partners to address a range of issues, including climate change (Brown 2010; Garfin et al. 2012; Western Governors' Association 2006, 2008, 2010). For example, the Western Federal Agency Support Team (WestFAST), which was established in 2008, created a partnership between the Western States Water Council (WSWC) and 11 federal agencies with water management responsibilities in the western United States. The agencies created a work plan in 2011 to address three key areas: 1) climate change; 2) water availability, water use, and water reuse; and 3) water quality. To date they have produced the WestFAST Water-Climate Change Program Inventory, the Federal Agency Summary, and a Water Availability Studies Inventory (http://www.westgov.org/wswc/WestFAST.htm).

The WSWC and the USACE produced the Western States Watershed Study (WSWS), which demonstrated how Federal agencies could work collaboratively with western states on planning activities (USACE 2009). In 2009, the WGA also adopted a policy resolution titled "Supporting the Integration of Climate Change Adaptation Science in the West" that created a Climate Adaptation Work Group composed of western state experts in air quality, forest management, water resources, and wildlife management. Other important adaptation actions were the SECURE Water Act in 2009, the Reclamation Colorado River Basin water supply and demand study, and the creation of NIDIS to support stakeholders in coping with drought (Hayes and Pulwarty 2012 ; U.S. Bureau of Reclamation 2011a, 2011b).

Illustrative Case Three: Climate Change Adaptation in Forests

Figure 28.6: Northwoods Climate Change Response Framework Region (Figure Source: USDA Forest Service 2012)

Northern Wisconsin's climate has warmed over the past 50 years, and windstorms, wildfires, insect outbreaks, and floods are projected to become more frequent in this century (Swanston et al. 2011). The resulting impacts on forests, combined with fragmented and complex forest ownership, create management challenges that extend across ownership boundaries, creating the need for a multi-stakeholder planning process (Joyce et al. 2009; Miles 2010; WDNR 2009, 2010).

To address these concerns, the Northern Institute of Applied Climate Science, the USDA's Forest Service, and many other partners initiated the Climate Change Response Framework to incorporate scientific research on climate change impacts into on-the-ground management. Originally developed as a pilot project for all-lands conservation in northern Wisconsin, it has expanded to cover three ecological regions (Northwoods, Central Hardwoods, and Central Appalachians) across eight states in the Midwest and Northeast. The Framework uses a collaborative and iterative approach to provide information and resources to forest owners and managers across a variety of private and public organizations. Several products were developed through the Framework in northern Wisconsin:

1. Vulnerability and mitigation assessments summarized the observed and projected changes in the northern Wisconsin climate; projected changes in forest composition and carbon stocks across a range of potential climates; and assessed related vulnerabilities of forest ecosystems in northern Wisconsin (Swanston et al. 2011).

2. *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers* (Swanston and Janowiak 2012) was developed to help managers identify management tactics that facilitate adaptation. A "menu" of adaptation strategies and approaches for planning, implementing, and monitoring adaptation activities was synthesized into an adaptation workbook from a broad set of literature and refined based on feedback from regional scientists and managers (Butler et al. 2011; Janowiak et al. 2012).

3. A series of adaptation demonstrations was initiated to showcase ground-level implementation. The Framework and adaptation workbook provide a common process shared by diverse landowners and a formal network that supports cross-boundary discussion about different management objectives, ecosystems, and associated adaptation tactics.

From the beginning, the Framework has taken an adaptive management approach in its adaptation planning and projects. Lessons learned include:

- Define the purpose and scope of the Framework and its components early, but allow for refinement to take advantage of new opportunities;
- Begin projects with a synthesis of existing information to avoid duplicating efforts;
- Plan for the extra time necessary to implement true collaboration;
- Carefully match the skills, commitment, and capacity of people and organizations to project tasks;
- Maintain an atmosphere of trust, positivity, and sense of adventure, rather than dwelling on failures;
- Acknowledge and work with uncertainty, rather than submit to "uncertainty paralysis";
- Recognize the necessity of effective communication among people with different goals, disciplinary backgrounds, vocabulary, and perspectives on uncertainty;
- Integrate the ecological and socioeconomic dimensions early by emphasizing the many ways that communities value and depend on forests; and
- Use technology to increase efficiency of internal communication and collaboration, as well as outreach.

The Framework brings scientists and land managers together to assess the vulnerability of ecosystems based on scientific information and experience in order to plan adaptation actions that meet management goals. On-the-ground implementation has just begun, and an increased focus on demonstrations, monitoring, and evaluation will inform future adaptation efforts.

Illustrative Case Four: Transportation, Land Use, and Climate Change: Integrating Climate Adaptation and Mitigation in Cape Cod, Massachusetts

Cape Cod, Massachusetts, a region of scenic beauty and environmental significance, is currently affected by sea level rise, coastal erosion, and localized flooding – impacts that are likely to be exacerbated by climate change (Volpe National Transportation Systems Center 2011a, 2011b). To address these concerns and help meet the state's greenhouse gas (GHG) reduction target (25% reduction based on 1990 levels by 2020), the DOT's Volpe Center worked with federal, regional, state, and local stakeholders to integrate climate change into existing and future transportation, land-use, coastal zone, and hazard mitigation planning through an initiative called the Transportation, Land Use, and Climate Change Pilot Project (Pilot Project) (Commonwealth of Massachusetts 2004; Volpe National Transportation Systems Center 2011a).

The process was initiated through an expert elicitation held in mid-2010 to identify areas on Cape Cod that are or could potentially be vulnerable to sea level rise, flooding, and erosion. The Volpe Center then used a geographic information system (GIS) software tool to develop and evaluate a series of transportation and land-use scenarios for the Cape under future development projections (ESRI 2011; Volpe National Transportation Systems Center 2011b). All scenarios were evaluated against a series of criteria that included: 1) reduction in vehicle miles traveled (VMT); 2) reduced greenhouse gas (GHG) emissions; 3) reduction in transportation energy use; 4) preservation of natural/existing ecosystems; 5) reduction in percentage of new population in areas identified as vulnerable to climate change impacts; and 6) increased regional accessibility to transportation (Volpe National Transportation Systems Center 2011a).

Once the preliminary scenarios were developed, a workshop was convened in which community and transportation planners, environmental managers, and Cape Cod National Seashore stakeholders selected areas for development and transit improvements to accommodate new growth while meeting the goals of reduced GHG emissions, increased resilience to climate change, and the conservation of natural systems (Volpe National Transportation Systems Center 2011b). Through interactive, visualization tools, participants were able to see in real-time the impacts of their siting decisions, allowing them to evaluate synergies and potential tradeoffs of their choices and to highlight areas where conflict could or already does exist, such as density enhancement in areas already or likely to be vulnerable to climate change (APA 2011). As a result, the stakeholders developed a refined transportation and land-use scenario that will support the region's long-range transportation planning as well as other local, regional, and state plans. This updated scenario identifies strategies that have climate adaptation and mitigation value, helping to ensure that the region simultaneously reduces its GHG footprint while building resilience to existing and future changes in climate (Volpe National Transportation Systems Center 2011a, 2011b). The overall success of the pilot project stemmed from the intensive stakeholder interaction at each phase of the project (design, implementation, and evaluation).

Traceable Accounts

Chapter 28: Adaptation

Key Message Process: A central component of the process were bi-weekly technical discussions held from October 2011 to June 2012 via teleconference that focused on collaborative review and summary of all technical inputs relevant to adaptation (130+) as well as additional published literature, the iterative development of key messages, and the final drafting of the Chapter. An in-person meeting was held in Washington, DC in June 2012. Meeting discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the lead author of each key message. Consensus was reached on all key messages and supporting text.

Key message #1/6	**Adaptation planning is occurring in the public and private sectors and at all levels of government, however, few measures have been implemented and those that have appear to be incremental changes.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the peer reviewed literature as well as the more than 130 Technical Inputs received and reviewed as part of the Federal Register Notice solicitation for public input. Numerous peer-reviewed publications describe that a growing number of sectors, governments at all scales, and private and non-governmental actors are starting to undertake adaptation activity (Garfin et al. 2012; Solecki and Rosenzweig 2012). Much of this activity is focused on planning with little literature documenting implementation of activities (Lackstrom et al. 2012; NRC 2010a; USGS 2012b). Supporting this statement is also plentiful literature that profiles barriers or constraints that are impeding the advancement of adaptation activity across sectors, scales, and regions (Horton et al. 2012; Marra 2012). Additional citations are used in the text of the adaptation chapter to substantiate this key message.
New information and remaining uncertainties	n/a
Assessment of confidence based on evidence	n/a

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Key Message Process: See key message #1.

Key message #2/6	**Barriers to implementation of adaptation action include lack of funding, policy and legal impediments, and difficulty in anticipating climate-related changes at local scales.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the peer reviewed literature as well as the more than 130 Technical Inputs received and reviewed as part of the Federal Register Notice solicitation for public input. A significant quantity of reviewed literature profiles barriers or constraints that are impeding the advancement of adaptation activity across sectors, scales, and regions (Horton et al. 2012; Marra 2012; NRC 2010a). Numerous peer-reviewed documents describe adaptation barriers (LINK TO CHAPTER TABLE 28.7). Moreover, additional citations are used in the text of the adaptation chapter to substantiate this key message.
New information and remaining uncertainties	n/a
Assessment of confidence based on evidence	n/a

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Key Message Process: See key message #1.

Key message #3/6	**There is no "one-size fits all" adaptation, but there are similarities in approaches across regions and sectors. Sharing best practices, learning by doing, and iterative and collaborative processes including stakeholder involvement, can help support progress.**
Description of evidence base	Literature submitted for the Assessment as well as additional literature reviewed by the author team fully supports the concept that adaptations will ultimately need to be selected for their local applicability based on impacts, timing, political structure, finances, and other criteria (Culver et al. 2012; NRC 2010a). Similarities do exist in the types of adaptation being implemented, although nuanced differences do make most adaptation uniquely appropriate for the specific implementer. The selection of locally and context-appropriate adaptations is enhanced by iterative and collaborative processes where stakeholders directly engage with decision makers and information providers (NPS 2010; NRC 2010a, 2010a). While there are no 'one-size fits all' adaptation strategies, evidence to-date supports the message that the sharing of best practices and lessons learned are greatly aiding in adaptation progress across sectors, systems, and governance systems (Lackstrom et al. 2012; Preston et al. 2011). Additional citations are used in the text of the adaptation chapter to substantiate this key message.
New information and remaining uncertainties	n/a
Assessment of confidence based on evidence	n/a

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Key Message Process: See key message #1.

Key message #4/6	Climate change adaptation actions often fulfill other societal goals, such as sustainable development, disaster risk reduction, or improvements in quality of life, and can therefore be readily incorporated into existing decision-making processes.
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the peer reviewed literature as well as the more than 130 Technical Inputs received and reviewed as part of the Federal Register Notice solicitation for public input. Literature submitted for the Assessment as well as additional literature reviewed by the author team support the message that a significant amount of activity that has climate adaptation value, is initiated for reasons other than for climate preparedness and/or has other co-benefits in addition to increasing preparedness to climate and weather impacts (Lackstrom et al. 2012; NRC 2009, 2010a; Preston et al. 2011). In recognition of this and other factors, a movement has emerged encouraging the integration of climate change considerations into existing decision-making and planning processes (i.e., mainstreaming) (EPA 2012; NRC 2010a; ORNL 2012b). Additional citations are used in the text of the adaptation chapter to substantiate this key message.
New information and remaining uncertainties	n/a
Assessment of confidence based on evidence	n/a

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Key Message Process: See key message #1.

Key message #5/6	**Vulnerability to climate change is exacerbated by other stresses such as pollution and habitat fragmentation. Adaptation to multiple stresses requires assessment of the composite threats as well as tradeoffs amongst costs, benefits, and risks of available options.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the peer reviewed literature as well as the more than 130 Technical Inputs received and reviewed as part of the Federal Register Notice solicitation for public input. Climate change is only one of a multitude of stresses affecting social, environmental, and economic systems. Activity to-date and literature profiling those activities support the need for climate adaptation activity to integrate the concerns of multiple stresses in decision-making and planning (IPCC 2007; NRC 2007; OTA 1993). As evidence by activities to-date, integrating multiple stresses into climate adaptation decision-making and vice versa will require the assessment of tradeoffs amongst costs, benefits, the risks of available options, and the potential value of outcomes (Culver et al. 2012; Needham et al. 2012) (ORNL 2012b). Additional citations are used in the text of the adaptation chapter to substantiate this key message.
New information and remaining uncertainties	n/a
Assessment of confidence based on evidence	n/a

Chapter 28: Adaptation

Key Message Process: See key message #1.

Key message #6/6	**The effectiveness of climate change adaptation has seldom been evaluated, because actions have only recently been initiated, and comprehensive evaluation metrics do not yet exist.**
Description of evidence base	The key message and supporting text summarizes extensive evidence documented in the peer reviewed literature as well as the more than 130 Technical Inputs received and reviewed as part of the Federal Register Notice solicitation for public input Numerous peer-reviewed publications indicate that no comprehensive adaptation evaluation metrics exist meaning that no substantial body of literature or guidance materials exist on how to thoroughly evaluate the success of adaptation activities (Hauser and Jadin 2012; Ingram et al. 2012; Lebow 2012; NRC 2010a). This is an emerging area of research. A challenge of creating adaptation evaluation metrics is the growing interest in mainstreaming; meaning that separating out adaptation activities from other activities could prove difficult. Additional citations are used in the text of the adaptation chapter to substantiate this key message.
New information and remaining uncertainties	n/a
Assessment of confidence based on evidence	n/a

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29. Research Agenda for Climate Change Science

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Overview

Investments in science-based assessments and policy-relevant research advance basic scientific understanding, as well as supporting, improving, and expanding response options (Clark et al. 2006). These investments also result in a range of opportunities for private sector interests who can develop more tailored decision-support products for customers. The research needs and gaps discussed in this chapter were identified during the development of the regional and sectoral technical input reports and through the contributions of the over 240 authors of the National Climate Assessment (NCA) chapters.

The U.S. Global Change Research Program's 2012-2021 Strategic Plan (USGCRP 2012) and the National Research Council's (NRC) study of America's Climate Choices offer important research goals that will provide information for decision makers to support developing, evaluating and executing plans to prepare for and respond to climate change. The USGCRP Sustained Assessment process is designed to provide a foundation for these efforts and for timely access to advances in scientific understanding. This chapter identifies important gaps in knowledge, synthesized into seven research goals with recommendations of high priority research needs to support the national assessment process and a range of international assessments, including the Intergovernmental Panel on Climate Change (IPCC) AR5, Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), regional assessments (for example, the Arctic Assessment), and topical assessments such as the International Assessment of Agricultural Knowledge, Science, and Technology for Development.

Since the focus of this chapter is on research needs identified through the national assessment process, it is not intended to cover the full range of goals of the USGCRP. There are many additional USGCRP priorities for climate change and global change science more broadly that are not reflected here.

Research Goal 1

Deepen understanding of the climate system, feedbacks, and impacts.

Fundamental climate science investments across a broad range of disciplines are critically important to understanding, and in some cases reducing, uncertainties about some of the physical processes of the climate system and the impacts of these changes. These investments also develop information at multiple temporal and spatial scales that can help decision-makers manage risk and take advantage of opportunities (the observations component of this issue is addressed in Research Goal 4). Assessing the potential consequences of a changing climate requires understanding the role of feedbacks, thresholds, extreme events, and abrupt changes that may disrupt natural and socioeconomic systems, as well as the implications of more gradual changes and also the degree and effectiveness of response actions.

Future assessments, particularly the sustained assessments of the USGCRP, will increasingly require improved projections of near- and long-term risks and opportunities for the nation. Integrated assessment and modeling tools can, if well designed, implemented, and communicated: a) enhance capacity to address economic, physical, and social impacts and ecosystems processes; b) support identification of efficient adaptation and mitigation policies and measures, including evaluation of policy alternatives, such as risk assessment and scenario development; and c) implement adaptation and mitigation policies and measures across many scales, but particularly at local and regional scales.

High priority research needs include:

- Better **understanding of important sources of uncertainty and feedbacks in the climate system** such as clouds, changes in land and sea ice, aerosols, land use and land cover, thresholds and feedbacks, and the means by which ocean dynamics affect changes in the climate system;

- Advancing capacity to project **biogeophysical changes in the nation's ecosystems and associated services** (such as food availability and security, protection of biodiversity, healthy wetlands, and abundant fresh water) or the nature, timing, and location of terrestrial permafrost and methane release processes;

- Improved understanding of the **interactions of climate change and natural variability** at multiple time scales, including seasonal to decadal changes (and consideration of the El Niño Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, etc.), extreme events (hurricanes, droughts, and floods), potential changes in ocean circulation related to climate change, and the global transfer of heat laterally and toward the poles;

- Improved, and more detailed, projections of the **rate of change in oceanic pH, carbonate saturation, and attendant acidification** and its consequences for the marine biosphere and food chain;

- Research to improve our nation's ability to understand **the cumulative and synergistic relationships between climate change and numerous human-caused stressors** at appropriate scales, including multiple stresses affecting the climate system (including concentrations of heat-trapping gases and particulates in the atmosphere, changes in land use and land cover, shifts in human cultural behavior or demographics, or changes in economic factors).

- Experiments on the effects of multiple stressors within and between social, physical, and ecological systems in the context of global change;

- Better understanding of the **potential for crossing thresholds** and tipping points in affected climate systems, along with development of indicators that allow for anticipation of abrupt changes and extreme events in the context of a changing climate.

- Assessing the **relative importance of different types of uncertainty** that affect various decision-making contexts, including uncertainties regarding vulnerability, different impacts models, future socioeconomic factors, possible changes in governance structures, decision-making protocols, and regional climate change.

- Better **long-term and regional scale projections of sea level changes**

- More specific regional information about the **role of soil moisture, groundwater recharge, and evapotranspiration in the hydrologic cycle** and water supply availability.

Research Goal 2

Develop local, regional, national, and international options to adapt to climate change.

Effectively and efficiently managing the risks and opportunities of current and projected climate change through adaptation requires understanding the risks posed by changing weather and climate patterns at local and regional scales, and who or what is exposed to those risks. This assessment and others, including the America's Climate Choices *Adapting to the Impacts of Climate Change* report (NRC 2010a) and Chapter 4 (on adaptation and mitigation options and responses) of the IPCC's AR4 Synthesis Report (IPCC 2007b), identified a broad set of research needs for understanding and implementing adaptation. These include research on adaptation processes, adaptive capacity, adaptation option identification and evaluation, and adaptive management of risks and opportunities. Important needs are geospatial assessments of vulnerability, research on the limits to, timing of, and tradeoffs in adaptation, and understanding of how adaptation interacts with mitigation activities, other stresses, and broader sustainability issues. Examples of high priority research needs include:

- Research on **best practices for adaptation planning and implementation** for federal, state, and local agencies, private firms, non-governmental organizations and local communities, including plans and actions to effectively manage risks due to climate change, and institutional frameworks to sustain adaptation efforts and enhance resilience over the long term;

- Evaluation of **alternative approaches to designing federally enabled clearinghouse(s)** with the capability to link decision-makers to adaptation tools, data, and expertise that support adaptation decision-making;

- Research that focuses on **adaptation processes and strategies** to better facilitate, evaluate (including evaluations of the effectiveness of adaptation), and coordinate adaptation within and across federal to local scales, across sectors and regions, and across public and private enterprises, recognizing the broad diversity of knowledge and research gaps that need to be addressed;

- Guidance on **appropriate use of information from global models as well as on various downscaling approaches** (statistical and dynamical), to assist decision-makers at local and regional scales with appropriate approaches to developing a range of projected future conditions for planning purposes;

- Research on **alternative institutional strategies to support adaptation,** including revisions to legal codes and policy practices;

- Enhancements of **understanding of synergies, trade-offs, and path dependencies between adaptation and mitigation** at local to national scales, over short- to longer-term time scales; and

- Better documentation of the rich history of adaptation activities over many centuries within Native American communities, leading to the potential for **integrating traditional knowledge and western science** in new and useful understanding of impacts, vulnerabilities, and adaptation strategies.

Research Goal 3

Explore options and actions that reduce the rate and magnitude of climate change.

Enhanced understanding of the interconnectedness of Earth and energy/economic systems will require research on the ways global-scale climate change is connected to energy strategies and global economic conditions. The NAS/NRC report on *Limiting the Magnitude of Climate Change* (NRC 2010c), in its America's Climate Choices study, recommended that the U.S. promptly develop and implement appropriate strategies that reduce GHG emissions. Examples of high priority research needs that build on this foundation include:

- Deepen understanding of the relationship between the fate of human-induced and natural carbon emissions, uptake by the terrestrial biosphere and oceans, and atmospheric concentrations, in order to **better understand the effectiveness and timescales of mitigation measures**;

- **Support socioeconomic analyses related to decision-making about land use, land management, water resources, associated ecological processes and services,** and how these sectors respond to changes in the climate system;

- **Test and expand understanding of the effects of different climate and integrated assessment model structures** and ways to categorize uncertainties in the supporting data;

- **Understand social, cultural, and behavioral processes that influence public understanding and motivations for individual and corporate mitigation actions**, including strategies and that increase resilience and flexibility in energy systems; and

- Understand the relationship between climate change, energy development, and water-dependent socioeconomic sectors to **inform national and state-level energy policies, aquifer utilization, and river agreements.**

Research Goal 4

Maintain, extend, expand, and improve the observations and data systems essential to understanding climate change and responding to it.

Our understanding and ability to assess changes in climate and other global processes is based on a comprehensive and sustained system of observations, monitoring, and data systems that document the history of climate and related changes on spatial scales relevant to regional and sectoral understanding and over many timescales. Additional effort is needed to ensure that the large data systems that bring together these observations are integrated and accessible in ways that increase utility of data for stakeholders. These observations include critical geophysical variables such as temperature, precipitation, and sea level rise, but also data on the processes that drive feedbacks (including social systems), mechanisms of abrupt change, atmospheric chemistry, solar radiation, and land use/land cover impacts. The data systems that bring together these observations need to be easily accessible to stakeholders, with clear communication of metadata, data quality, and uncertainties. High priority data needs include observations, monitoring, and indicator capabilities focused on data-poor regions, poorly documented socioeconomic and health-related factors, and under-observed regional and sectoral data; important measurements of system resilience; and data for sensitive systems, including social systems, that currently do not have adequate temporal or spatial resolution for vulnerability analysis and decision support.

Examples of high priority research needs include:

- **Evaluation of the data needs, potential components, and structure of a national indicator system**. Indicators can support understanding of changes in the rate of global change, progress in adaptation/response efforts, and communication of climate change risks and opportunities. Indicators could include trends and changes in land use, air and water pollution, water supply and demand, vector borne disease, coastal and ocean conditions (acidification, sea level, ocean stratification, temperatures, salinity, and ecosystem health), snow, sea ice conditions, ice sheets and glacier melt rates, public health, and agronomic data, for example; indicators are critically needed to assess progress in adaptation and response efforts, a "grand challenge" for integrated physical and social science; and

- **Prioritizing investments in observations and data systems** that are designed to support responses to climate change, including, for example, efforts to limit emissions, monitor public health, sequester carbon, and implement adaptation strategies. This requires establishing baseline conditions, specifying spatial detail and temporal frequency of observations, and setting standards for metadata, interoperability, and regulatory and voluntary reporting, such as those outlined in the Informing Effective Responses Report of the NRC/NAS Americas Climate Choices series (NRC 2010b).

Research Goal 5

Inform and enable decision-makers to address the challenges of climate change and its consequences.

There is a growing demand from leaders in both the public and private sectors for better dissemination of climate-relevant information and more effective ways to support climate-related decisions. Critical gaps in knowledge relative to decision support include the variety of socioeconomic issues that affect the capacity of individuals and communities to use the best available scientific information in support of decision-making, including the need to understand risk perception as a motivator for taking actions that reduce risk.

There are also numerous instances where policy barriers, institutional capacity or structure, or conflicting laws and regulations are noted. For instance, Chapter 12 (Impacts of Climate Change on Tribal/Indigenous and Native Lands and Resources) notes that there is no institutional framework for addressing responses of the magnitude of village relocation in Alaska, and Chapter 3 (Water Resources) points out that existing water management institutions may be inadequate in the context of rapidly changing conditions. These instances point to a need to evaluate whether the existing legal and regulatory structures, largely developed to address specific issues in isolation, can adequately respond to the highly interconnected issues associated with climate change. There will be a growing need to more thoroughly consider problems that are different in kind rather than magnitude. The extent to which our existing structures and expertise are capable of responding effectively is unclear and represents a significant gap in our knowledge.

High priority research needs include:

- Research to support **risk-based decision processes, including more effective means to communicate interactions of multiple stresses and levels of scientific confidence and uncertainty.** High priority research on social processes includes transferable vulnerability assessment techniques, evaluation methodologies, improved understanding of consumption patterns and environmental consequences, effective resource management institutions, iterative risk management, and social learning and adaptive processes;

- Research into and assessment of **decision-maker information needs** within regions and sectors and the methods and tools to meet those needs;

- Research on how to increase the **effectiveness of processes and practices designed to inform decisions across regions and sectors**, including strategies for managing carbon, early warning systems, climate and drought information services, and the analyses of legal, regulatory, and policy approaches that support adaptation and mitigation efforts in the context of a non-stationary climate;

- Improved and expanded efforts **at characterizing the costs and benefits of mitigation and adaptation actions,** including economic and non-economic metrics that evaluate the costs of action versus the costs of inaction;

- Development of **methodologies and baseline information to support evaluation of completed and ongoing adaptation, mitigation, and assessment efforts**; and

- Studies of the **capacity of existing institutions and regulatory strategies to function in the context of a changing climate,** and ways to develop more flexible and integrated management approaches**.**

Research Goal 6

Capacity Building, Education, and Workforce Development

Building human capacity to respond to the emerging challenges described in this Assessment requires expansion of skills within the existing public and private sectors and developing a new workforce that excels at critical and interdisciplinary thinking. Useful capacities include facilitation and communications skills, integration of new technologies and data sources into existing programs and practices, management of collaborative processes to allow for imaginative solutions, development and use of sustainable technologies to reduce climate risks, and building frameworks for decision-making in an internationally interdependent world. A deeper understanding of such matters as evaluations of processes and impacts of climate change, disaster risk reduction, energy policy impacts, ecosystem services and biodiversity, poverty reduction, food security, and sustainable consumption require new approaches to training and curriculum, as well as research to evaluate the effectiveness of different approaches to research and teaching.

Examples of recommended research include:

- Research into new **approaches to education of the existing and future workforce** and training in the professions, including evaluation of the best ways to educate the next generation in the fields of science (natural, physical, and social), technology, engineering, and mathematics (STEM) and related fields of study (such as business, law, medicine, and other relevant professional schools). Ideally, such training would include a deeper understanding of the climate system, natural resources, energy policy options, and economic sustainability;

- Investigations of effective approaches to developing a more climate-informed civil society, including **alternative media and methods for communication**; and

- Research on improving **STEM education and training programs at Native American colleges and universities and other similar institutions** to increase capacity to carry out climate change impact and adaptation plans.

Research Goal 7

Enhance scenarios to include essential attributes of coupled human and natural systems.

Scenarios are important tools that help with analysis of climate drivers and the effects of management and policy decisions. They provide the scientific research and assessment communities with the capability to: a) evaluate the governing conditions (such as timing and rates of change in concentration of greenhouse gases and aerosols) in the atmosphere that might unfold under specific socioeconomic conditions and technological and environmental options; b) assess the natural response of the Earth system and the potential impacts and consequences of a range of future climates; and c) evaluate the implications of different approaches to mitigation and adaptation (Moss et al. 2010). Stakeholders and scientists identified a need for more fully developed scenario-building capabilities that better enable assessments at regional to more local scales on timeframes of relevance to policy and decision-making.

The IPCC has led in the development of scenarios to support international scientific work of the three IPCC Working Groups, and it made major progress with the release in 2000 of the Special Report on Emissions Scenarios (SRES)(IPCC 2000). Historically, scenarios have been used for analyzing global-scale trends (IPCC 2007a) that include a range of demographic changes, social and economic conditions, and technological options. These can be used to project emissions and other inputs to Global Climate Models/General Circulation Models (GCMs). A new scenario process is underway within IPCC that will facilitate more regional/local assessments through finer scale models.

Examples of research needs related to scenario development include:

- **Using components of the new scenarios to enhance** understanding of the implications of a changing climate at more regional scales and to support international climate negotiations, especially where a focus on smaller geographic scales and sectoral levels, such as coastal sea level, land use and land cover change, and socioeconomic conditions, will be important;

- **Developing new methods, tools, and skill to apply scenarios to policy development at local levels**, to broaden civil society's understanding of a changing climate, and provide ways and means to expand education and training capacities for the nation (for example, the Global Business Network's Four Quad Scenario planning methodology that has been used by the U.S. Park Service (GBN 2012));

- **Providing scenario-based guidance to stakeholders** who want to understand climate variability and change in the near- and longer-term in order to support them in their decisions and policies; and

- **Ensuring that socioeconomic, land use, water resource, and climate scenario information is available** in a timely way for future assessment processes.

Conclusions

This chapter includes research recommendations on a number of broad topics. Addressing the important research recommendations identified in this chapter will enhance knowledge of the intersection of human and natural systems in the context of climate change – knowledge that is needed for regional, national, and international policy development and decision-making. Expanding scientific understanding and responding to the needs of decision-makers at multiple scales will require integrated research activities across sectoral, regional, and temporal scales.

Traceable Accounts

Chapter 29: Research Agenda

Chapter Process:

The author team asked each of the other chapter author teams to identify important gaps in knowledge and key research needs that they identified in the course of writing their chapters. In addition to the lists provided by each chapter author team, the team also drew on analyses from over 40 technical inputs provided by the public, and a wide variety of technical and scholarly literature, especially the U.S. Global Change Research Program's Strategic Plan (USGCRP 2012) and the National Research Council's America's Climate Choices (NRC 2011), to compile a potential research agenda. Using expert deliberation, including a number of teleconference meetings and email conversations among author team members, the author team agreed on high-priority research needs, organized under seven synthetic research goals.

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30. Sustained Assessment

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A New Vision for Future U.S. Assessments

A primary goal of the U.S. National Climate Assessment (NCA) is to help the nation anticipate, mitigate, and adapt to impacts from national and global climate change, including changes in climate variability. Since 1990, when Congress authorized the U.S. Global Change Research Program (USGCRP) through the Global Change Research Act (GCRA 1990) and required periodic updates on climate science and its implications, researchers from many fields have observed significant climate change impacts in every region of the U.S. The accelerating pace of these changes, as well as scenario-based projections for future climate changes and effects, is articulated in this third national climate assessment.

As the third NCA synthesis report was being prepared, a vision for a new approach to future assessments took shape: a "sustained assessment" process. The vision includes an ongoing process of working to understand and evaluate the nation's vulnerabilities to climate variability and change and its capacity to respond. A sustained assessment, in addition to producing periodic synthesis reports as required by law, recognizes that the ability to understand, predict, assess, and respond to rapid changes in the global environment requires ongoing efforts to integrate new knowledge and experience. It accomplishes this by: 1) building foundational knowledge and collecting relevant data; 2) developing targeted scientific reports and other products that respond directly to the needs of agencies, decision-makers, and end users; and 3) creating a framework for continued interactions between the assessment partners and stakeholders and the scientific community.

To provide decision-makers with more timely, concise, and useful information, a sustained assessment process would include both ongoing, extensive engagement with public and private partners and targeted, scientifically rigorous reports that address concerns in a timely fashion. A growing body of assessment literature has guided and informed the development of this approach to a sustained assessment (Cash and Moser 2000; Clark et al. 2006; Farrell and Jager 2005; Mitchell 2006; NRC 2007).

The envisioned sustained assessment process includes continuing and expanding engagement with scientists from government, academia, business, and non-governmental organizations. These partnerships broaden the scientific base from which conclusions can be drawn. In addition, sustained engagement with decision-makers and end users helps scientists understand what information society wants and needs, and it provides mechanisms for researchers to receive ongoing feedback on the utility of the tools and data they provide.

An ongoing process that supports these forms of outreach and engagement allows for more comprehensive and insightful evaluation of climate changes across the nation, including how decision-makers and end users are responding to these changes. The most thoughtful and robust responses to climate change can be made only when these complex issues, including the underlying science and its many implications for the nation, are documented and communicated in a way that both scientists and non-scientists can understand.

This sustained assessment process will lead to better outcomes for the people of the United States by providing more relevant, comprehensible, and usable knowledge to guide decisions related to climate change at local, regional, and national scales. Additional details about the components of the sustained assessment process will be provided in the first special report of the National Climate Assessment and Development Advisory Committee (*ref when complete*).

Contributions of a Sustained Assessment Process

A sustained assessment process will not only include producing the periodic scientific assessment reports required by the 1990 GCRA, but it also will enable many other important outcomes. A well designed and executed sustained assessment process will:

1. Increase the nation's capacity to measure and evaluate the impacts of and responses to further climate change in the United States, locally, regionally, and nationally.
2. Improve the collection of critical data, access to that data, and the capacity of users to work with datasets relevant to their specific issues and interests.
3. Support the creation of the first integrated suite of national indicators of climate-related trends across a variety of important climate drivers and responses.
4. Catalyze the production of targeted, in-depth special assessment reports on sectoral topics (for example, agriculture), cross-sectoral topics (for example, the connection between water and energy production), regional topics, and other topics that will help inform Americans' climate choices about mitigation and adaptation. These reports will generate new insights about climate change, its impacts, and the effectiveness of societal responses. Special reports also can focus on improvements to specific aspects of the process (for example, scenarios, indicators, and data systems) to reinforce the foundation for the overarching but necessarily more constrained periodic synthesis reports.
5. Create a network of scientific, decision-maker, and user communities for extended dialogue and engagement regarding climate change.
6. Provide a systematic way to identify gaps in knowledge and uncertainties faced by the scientific community and by U.S. domestic and international partners and to set priorities for their resolution.
7. Develop and apply tools to evaluate progress and guide improvements in processes and products over time. This will support an iterative approach to managing risks and opportunities associated with changing global and national conditions.

Assessments facilitate the collection of different kinds of information that can be integrated to yield new and useful scientific insights. The vision for the sustained assessment process is to continue to build knowledge about the intersection of human and natural systems to better understand the risks and opportunities of global change at multiple spatial and temporal scales. The sustained assessment process also can help define the range of information needs of decision-makers and end users relative to adaptation and mitigation, as well as the associated costs of impacts and benefits of response actions. Moreover, it is by its very nature a continuous process, uniquely positioned to support an iterative, risk-based approach to adaptation.

Finally, although a sustained assessment process allows for ongoing improvements in products and processes, it also requires underlying support systems. These can include access to observational data sources, information management systems, and support networks such as the Global Change Information System (GCIS; see below). Other fundamental infrastructure for assessments includes integrated assessment models, climate model inter-comparison projects, data streams (for example, emissions data or socioeconomic data), processes for building scenarios and deploying them at critical junctures in the assessment process, and evaluation systems.

Assessment Capacity

Scientific assessments require substantial scientific expertise and judgment, involving skills atypical of those required for typical research (Farrell and Jager 2005; Mitchell 2006; NRC 2007). Assessment capacity includes engaging knowledgeable and experienced people, developing networks to promote interactions, identifying and mentoring new scientific talent, and building in-depth understanding of a variety of economic, technical, and scientific topics. Building and maintaining capacity through all of these approaches is therefore critical to the smooth and efficient functioning of the assessment process.

Sustained interactions among scientists and stakeholders have consistently been shown to improve the utility and effectiveness of assessment processes and outcomes (NRC 2007) and to facilitate the development of decision support tools (CCSP 2008). A sustained assessment provides the necessary coordination and infrastructure needed to maintain an ongoing dialog among producers and users of information so that decision-makers can manage risks and take advantage of opportunities more efficiently. This provides the capacity and flexibility to react to, and take advantage of, rapidly advancing developments in climate science and changing conditions in order to improve the utility and timeliness of future synthesis reports.

Data Collection, Access, and Analysis

Credible scientific information is needed on an ongoing basis to support fundamental understanding of the climate system and its interactions with ecological, economic, and social systems, and for the development of adaptation and mitigation strategies. Improved systems for data access can more effectively meet the requests of stakeholders for accessible, relevant, and timely information. An ongoing process can build a more complete information base related to climate change related impacts and vulnerabilities, and it can result in more sophisticated scientific analyses that support the mandated quadrennial synthesis reports in a more efficient and effective manner. Selecting which data to collect and analyze is a critical component of assessments of change.

The sustained assessment process will facilitate the development and maintenance of a web-based assessment information discovery, access, and retrieval system that facilitates easy access to a range of information for those who need it, in a timely and authoritative manner (the GCIS of the USGCRP). A major short-term goal is to provide transparent and highly linked access to the data used to support conclusions in the third NCA report, but this is only the first step in a much larger effort.

Indicators

Indicators are measurements or calculations that represent important features of the status, trends, or performance of a system (such as the economy, agriculture, natural ecosystems, or changes in Arctic sea ice cover). Indicators are used to identify and communicate changing conditions to inform both research and management decisions (NRC 2000). The NCA indicator system is intended to focus on key aspects of change – as well as vulnerabilities, impacts, and states of preparedness – to inform decision-makers and the public. In the context of ongoing assessment activities, these indicators can be tracked to provide timely, authoritative, and climate-relevant measurements regarding the status, rates of change, and trends of key physical, ecological, and societal variables.

Special Reports

As currently envisioned, the sustained assessment process also paves the way for special reports that help inform local, regional, and sectoral mitigation and adaptation activities and provide a foundation for more useful and more comprehensive periodic synthesis reports. Completing in-depth assessments of national or regional importance and providing a constantly improving foundation for the periodic synthesis reports provides for significant flexibility and enhanced policy relevance. In addition, these special reports also can investigate emerging issues of concern or help decision-makers understand the trade-offs among different courses of action. Even more focused reports and activities that emerge from ongoing assessment activities can blend the objectives of incorporating the latest science with responding relatively quickly to the most pressing stakeholder and government needs. Finally, special reports also can be produced on scenarios of climate change, sea level rise, demography, land-use change, and other issues critical to the assessment process.

A Network to Foster Partnerships, Encourage Engagement, and Develop Solutions

The USGCRP has long recognized the importance of partnerships, two-way communication, and ongoing and meaningful engagement (USGCRP 2012). The five National Research Council (NRC) *America's Climate Choices* reports published in 2010 and 2011 also underscore the essential nature of this engagement (for example, see NRC 2010). Partnerships and engagement strategies among federal and non-federal participants are needed to: 1) communicate effectively about the assessment, including its products and processes and their relevance as actionable information (Moser and Dilling 2011); 2) encourage participation and knowledge sharing; 3) create opportunities for meaningful engagement of end users and public and private decision-makers to inform the substance of the assessment; and 4) offer opportunities for input, direction, review, and feedback.

An important component of the new sustained assessment vision is NCAnet: a "network of networks" that helps to communicate the NCA process and products to a broader audience. This network of partner organizations, including private sector, government, non-governmental organizations, and professional societies, leverages resources and facilitates communication and partnerships. NCAnet can assist in developing and supporting diverse science capabilities and assessment competencies within and outside of the federal government.

Evaluation of the Process

Ongoing evaluation of assessment processes and products, as well as incorporating the lessons learned over time, is a specific objective of the USGCRP Strategic Plan (USGCRP 2012). Evaluation efforts are considered integral for enabling learning and adaptive management of the assessment process, measuring the ability to meet both legally required objectives and strategic goals, maintaining institutional memory, and improving the assessment process and its contributions to scientific understanding as well as to society. Ongoing improvements in the assessment process also will support an iterative approach to decision making in the context of rapid change.

Recommendations on Research Priorities

The GCRA requires regular evaluations of gaps in knowledge and assessments of uncertainties that require additional scientific input. A sustained assessment process provides for regular updates on science needs to the USGCRP's annual research prioritization process, as well as to the triennial and decadal revisions to its research plan.

Traceable Account

Chapter 30: Sustained Assessment

Key Message Process:

Planning for the sustained assessment process and including a description of the process in a chapter of the third NCA synthesis report began as soon as the report process was launched, with mechanisms for creating and implementing a sustained process included as key discussion points in early NCA process workshops (USGCRP 2010a, 2010b, 2010c). Prior to the formation of the chapter author teams, the need for a sustained assessment was described in the NCA Strategy Summary (USGCRP 2011). The amended charter for the National Climate Assessment and Development Advisory Committee (NCADAC) specifies that the NCADAC is to provide advice and recommendations toward the development of an ongoing, sustainable national assessment of global change impacts and adaptation and mitigation strategies for the Nation. To that end, NCADAC formed a working group on sustained assessment, and the USGCRP Interagency National Climate Assessment Working Group (INCA) made this topic a priority in their regular meetings. The USGCRP also established "conduct sustained assessments" as one of four programmatic pillars in its recent Strategic Plan (USGCRP 2012).

The sustained assessment author team drew on a wide variety of source materials in framing the need for a sustained assessment process, including calls in both previous National Climate Assessment reports (Karl et al. 2009; NAST 2000) and in several publications from the National Research Council (NRC 2007, 2009, 2010) that focused specifically on the National Climate Assessment. The author team also considered a rich literature on assessments in general (for example, (Farrell and Jager 2005; Mitchell 2006). In developing the chapter describing the sustained assessment process, the author team first worked with the NCADAC, especially the NCADAC working group on sustained assessment, and the INCA to develop a vision for sustained assessment and a list of activities required to implement this vision. They then collected feedback from each of the chapters' coordinating lead authors, agencies, chairs of other NCADAC working groups, and targeted stakeholders. Drawing on these comments and the knowledge bases cited above, the author team came to consensus on the objectives and categories of activities provided in the chapter using teleconference and email discussions. The NCADAC is currently forming a new author team to produce a longer special report on the sustained assessment process.

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Appendix: NCA Climate Science — Addressing Commonly Asked Questions from A to Z

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Introduction

This section answers some commonly asked questions about climate change. These answers are based on peer-reviewed science and assessments and have been confirmed by multiple analyses.

Outline of the Questions addressed

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

B. Is the climate changing? How do we know?

C. Climate is always changing. How is recent change different than in the past?

D. Is the global temperature still increasing? Isn't there recent evidence that it is actually cooling?

E. Is it getting warmer at the same rate everywhere? Are these trends likely to continue?

F. How long have scientists been investigating human influences on climate?

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

H. Could the Sun or other natural factors explain recent climate changes?

I. How do we know that human activities are the primary cause of recent climate change?

J. What is and is not debated among climate scientists about climate change?

K. Is the global surface temperature record good enough to determine whether climate is changing?

L. Is Antarctica gaining or losing ice? What about Greenland?
M. What about global cooling predictions in the 1970s?
N. How is climate projected to change in the future?
O. Does climate change affect severe weather?
P. Are the oceans affected by climate change?
Q. What is ocean acidification?
R. Should we trust the computer models of the Earth's climate?
S. What are the key uncertainties about climate change?
T. Are there tipping points in the climate system we should be concerned about?
U. Why should I care? How is climate change going to affect us?
V. Won't more warming be good for us?
W. Who will be most affected by climate change?
X. What can be done? Are there solutions?
Y. Is it better to act now or later?
Z. Can we reverse global warming?

Questions and Answers

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

We are all familiar with weather. Weather is the day-to-day and even year-to-year variations in temperature, precipitation, and other aspects of the atmosphere around us. From a scientific perspective, it is impossible to predict weather past about two weeks. From a practical perspective, state-of-the-art numerical weather prediction is very accurate for a few days to a week in advance.

If weather cannot be predicted even a few weeks into the future, how can scientists project the future climate decades in the future? Weather is made up of individual events; climate is the long-term statistics of those events. Just like individual people, individual events are difficult and often even impossible to predict. However, it is possible to predict the behavior or statistics of large groups of people: assessing the occurrence of diabetes or the risk of automobile accidents for a given population, for example, even though we cannot say which particular individuals will be affected. In the same way, it is also possible to estimate changes in the statistics of a large number of weather events, especially when we know what is causing them to change.

Climate is how the atmosphere behaves over relatively long periods of time, usually taken as the statistics of weather over time scales of 30 years or more. Climate is primarily the result of the local effects of geographic location (for example, whether you live in the mountains or near the ocean) combined with large-scale climate factors, including the energy received from the sun and levels of heat-trapping gases in the atmosphere. "Climate change" refers to changes in the long-term averages and variations in weather.

We know how these have changed in the past and can successfully explain the climate change that has already occurred. Because we understand the physics of how the atmosphere works relatively well, we use the same approach to estimate how the climate will change in the future in response to a given increase in human emissions of heat-trapping gases, or natural changes such as variations in energy from the Sun.

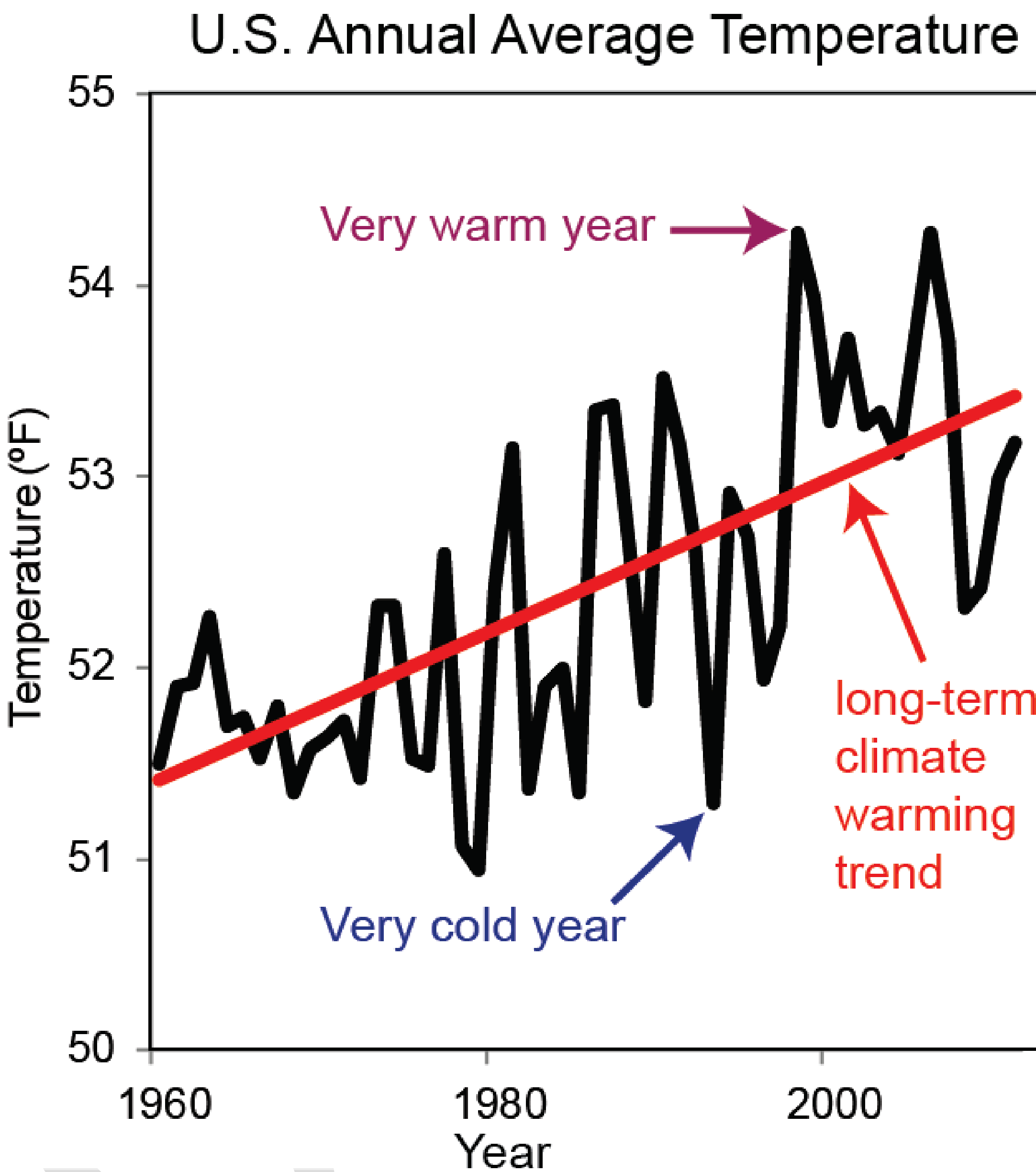

Figure 1: U.S. Annual Average Temperature

Caption: Day-to-day weather does not tell us much about climate. One cold day, or even a cold year, does not contradict a long-term warming trend, and one hot year does not prove it. Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. (Figure source adapted from Kunkel et al. 2012)

B. Is the climate changing? How do we know?

There is no question that the world has warmed since the 1800s. Evidence abounds, from the top of the atmosphere to the depths of the oceans. Changes in surface, atmospheric, and oceanic temperatures; glaciers, snow cover, and sea ice; sea level; and atmospheric water vapor have been documented by hundreds of studies conducted by many scientists in countries around the world.

Documenting climate change often begins with global average Earth surface temperatures, which formed the basis for the IPCC's conclusion in 2007 that the "warming of the climate system is unequivocal." Temperatures recorded by weather stations, however, are only one indicator of climate change. Broader evidence for a warming world comes from a wide range of physically consistent measurements of the Earth's climate system.

Ten Indicators of a Warming World

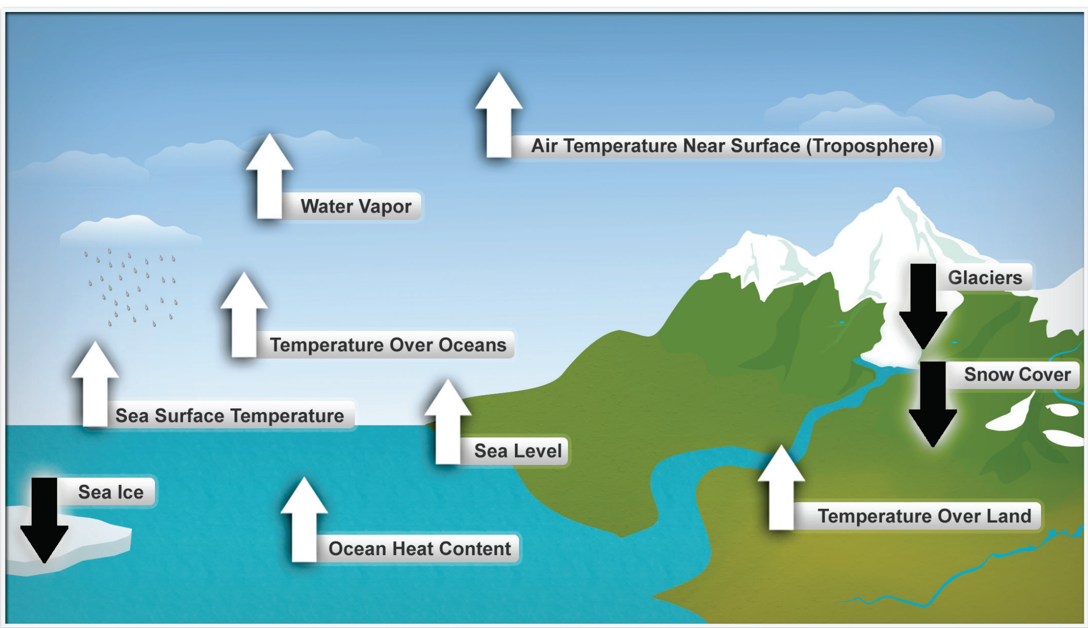

Figure 2: Ten Indicators of a Warming World

Caption: Long-term observations of many aspects of the Earth's climate show changes consistent with a warming world. Upward and downward arrows in the diagram indicate recently documented increases and decreases, respectively. (Figure source: NOAA NCDC)

Observed warming is not confined to the Earth's surface. Measurements by weather balloons and satellites consistently show that the temperature of the troposphere, the lowest layer of the atmosphere, has increased. The upper ocean has warmed, and more than 90% of the energy absorbed by the climate system since the 1960s has been stored in the oceans. As the oceans warm, seawater expands, causing sea level to rise.

Warmer air will, on average, contain a greater quantity of water vapor. Globally, analyses show that the amount of water vapor in the atmosphere has also increased over the land and the oceans.

About 90% of the glaciers and land-based ice sheets worldwide are melting as the Earth warms, adding further to the sea level rise. Spring snow cover has decreased across the Northern Hemisphere since the 1950s. There have been substantial losses in sea ice in the Arctic Ocean, particularly during the summer minimum in extent (see CAQ L for discussion of Antarctic sea ice).

All of these indicators and all of the independent data sets that have been assembled unequivocally point to the same conclusion: from the ocean depths to the top of the troposphere, the world has warmed. The upper atmosphere, specifically the stratosphere, has cooled, just as expected from the radiative effects of the increasing levels of carbon dioxide due to human activities, predominantly the burning of coal, oil, and natural gas.

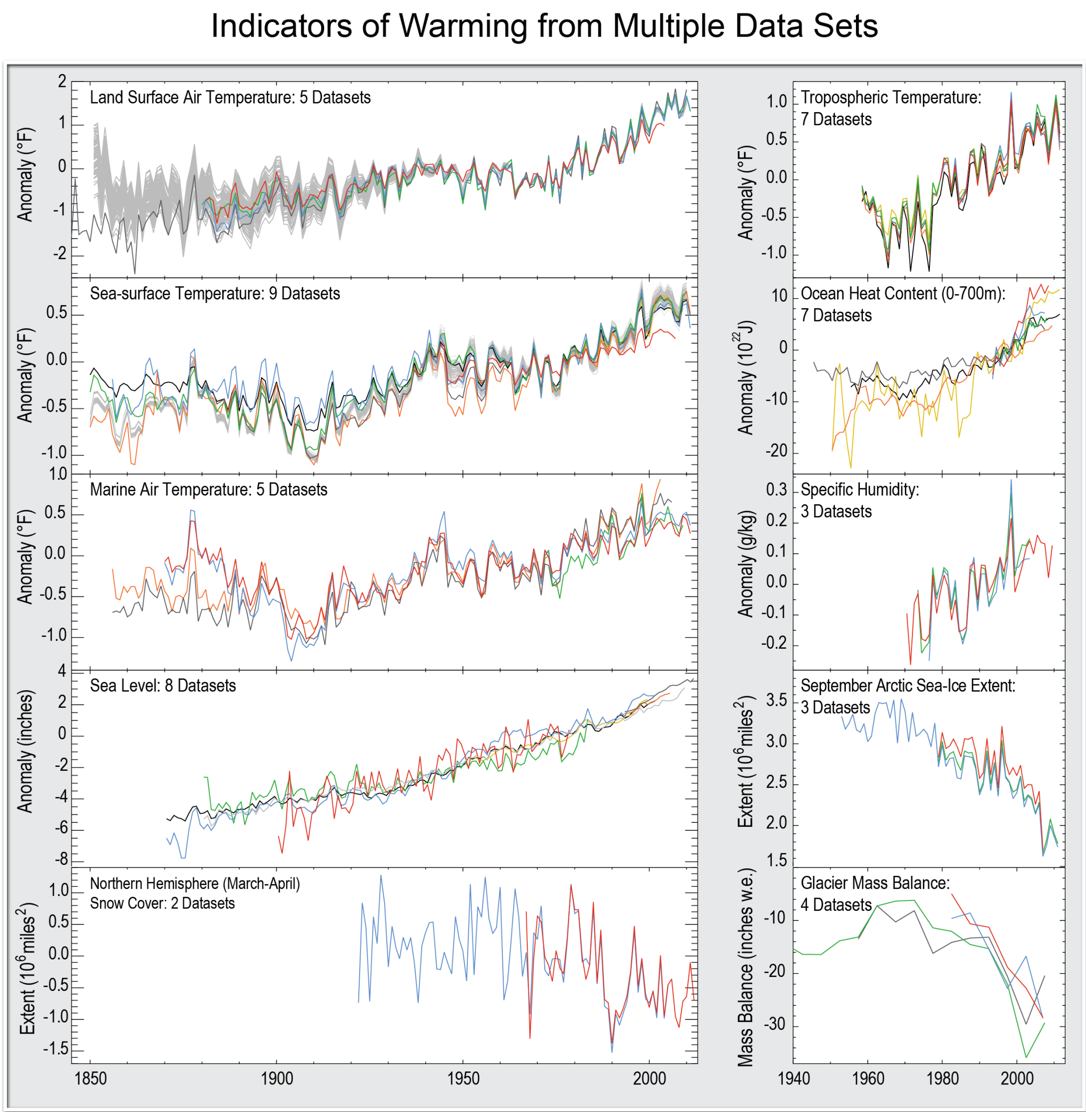

Figure 3: Indicators of Warming from Multiple Data Sets

Caption: There are multiple datasets documenting changes in climate indicators, all consistent in supporting the conclusion of a warming planet. (Figure source: Kennedy et al. 2010)

C. Climate is always changing. How is recent change different than in the past?

The Earth has experienced many large climate changes in the past. However, current changes in climate are unusual for two reasons: first, these changes are occurring faster than most past changes in the Earth's climate; second, these changes are primarily the result of human activities.

In the past, climate change was driven exclusively by natural forcings: explosive volcanic eruptions that inject reflective particles into the upper atmosphere, changes in energy from the Sun, and periodic variations in the Earth's orbit. Natural cycles that transfer heat between the ocean and the atmosphere, as well as slowly changing natural variations in heat-trapping gases in the atmosphere have also all altered global average temperature over periods ranging from months to millennia. Specifically, natural changes in atmospheric levels of heat-trapping gases have amplified the effects of natural influences on global temperature. For example, past glacial periods were initiated by shifts in the Earth's orbit, but amplified by decreases in atmospheric levels of carbon dioxide and by greater reflection of solar radiation by ice and snow as the Earth's climate system responded to a cooler climate. Some periods in the distant past were even much warmer than what scientists predict will occur from human-induced global warming over this century. But these changes in the distant past generally occurred much more slowly than current changes.

Natural factors are still affecting the planet's climate today. The difference is that, since the beginning of the Industrial Revolution, humans have been adding increasing amounts of heat-trapping gases to the atmosphere at a much faster rate than can occur naturally. Records from ice cores, tree rings, soil boreholes, and other forms of "natural thermometers," or "proxy" climate data, reveal three important findings. First, recent climate change is unusually rapid. After a glacial maximum, the Earth typically warms by about 7ºF to 13ºF over thousands of years. The current rate of warming is about 8 times faster.

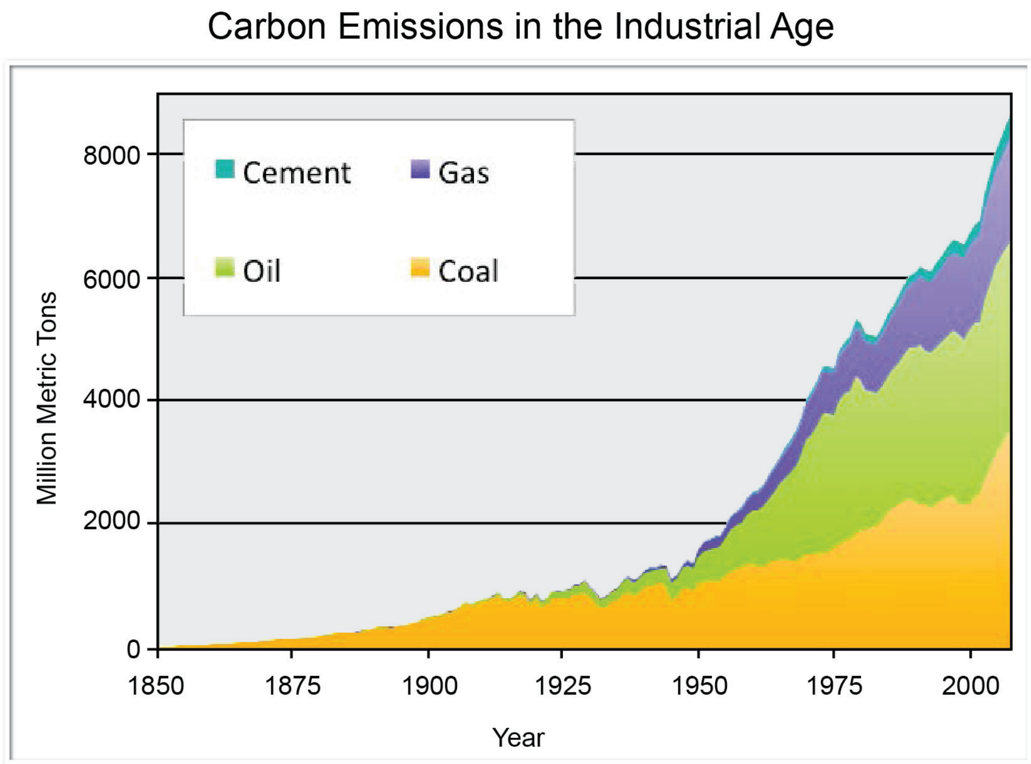

Figure 4: Carbon Emissions in the Industrial Age

Caption: Carbon emissions from burning coal, oil, and gas and from producing cement, in units of million metric tons of carbon. (Source: Boden et al. 2010)

Second, global temperatures in the last 100 years are unusually high when compared to temperatures over the last several thousand years. And third, carbon dioxide levels are currently higher than any time in at least the last 800,000 years. Paleoclimate studies indicate that temperature and carbon dioxide levels have been higher in the distant past, millions of years ago, when the world was very different than it is today. But never before have such rapid, global-scale changes occurred during the history of human civilization.

The fact is that human civilization didn't exist during previous warm periods. Our societies have not been built to withstand the changes that are anticipated in the relatively near future, and many are already experiencing the effects of higher temperatures, sea level rise, and other climate change-related impacts.

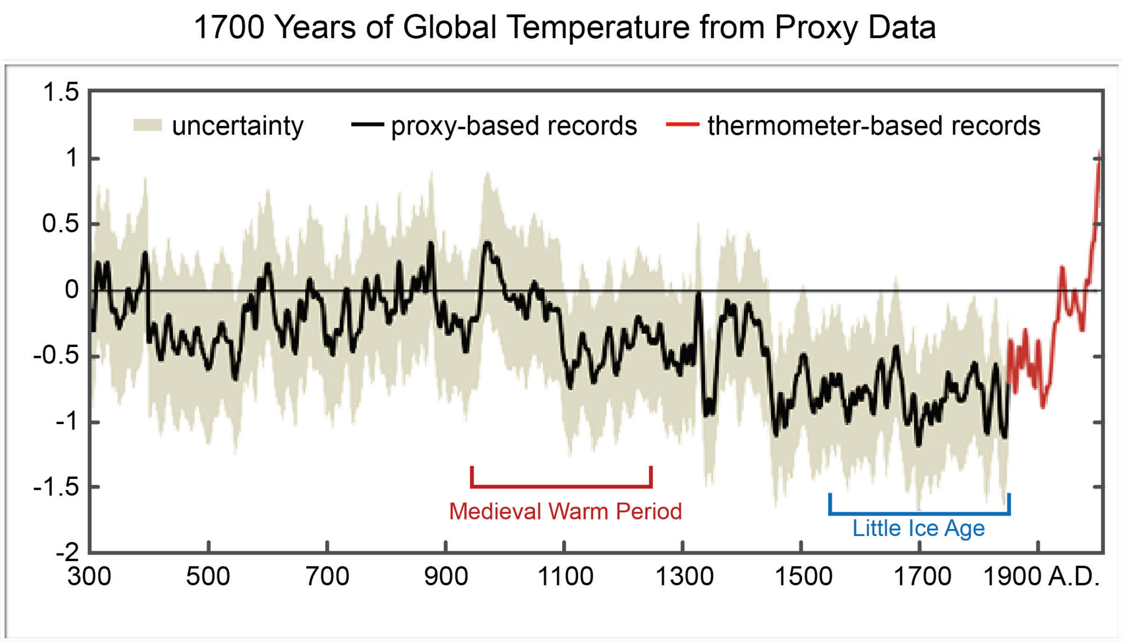

Figure 5: 1700 years of Global Temperature from Proxy Data

Caption: Temperature data for the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented in gray). These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years, and that the last decade was the warmest decade. (Adapted from Mann et al. 2008)

D. Is the global temperature still increasing? Isn't there recent evidence that it is actually cooling?

Climate change is defined as a change in the average conditions over periods of 30 years or more (see CAQ A.). On these time scales, global temperature continues to increase. Over shorter time scales, however, natural variability (due to the effects of El Niño and La Niña events in the Pacific Ocean, for example, or volcanic eruptions or changes in energy from the Sun) can reduce the rate of warming or even create a temporary cooling.

From 1970 to 2010, for example, global temperature trends taken at five-year intervals range from decreases to sharp increases. The most recent five-year period, from 2005 to 2010, included the largest solar minimum experienced since the Little Ice Age of the late 1700s and also occurred during a period when natural cycles were causing greater than average amounts of heat to be taken up by the oceans. These natural factors contributed to a temporary downward trend in temperature.

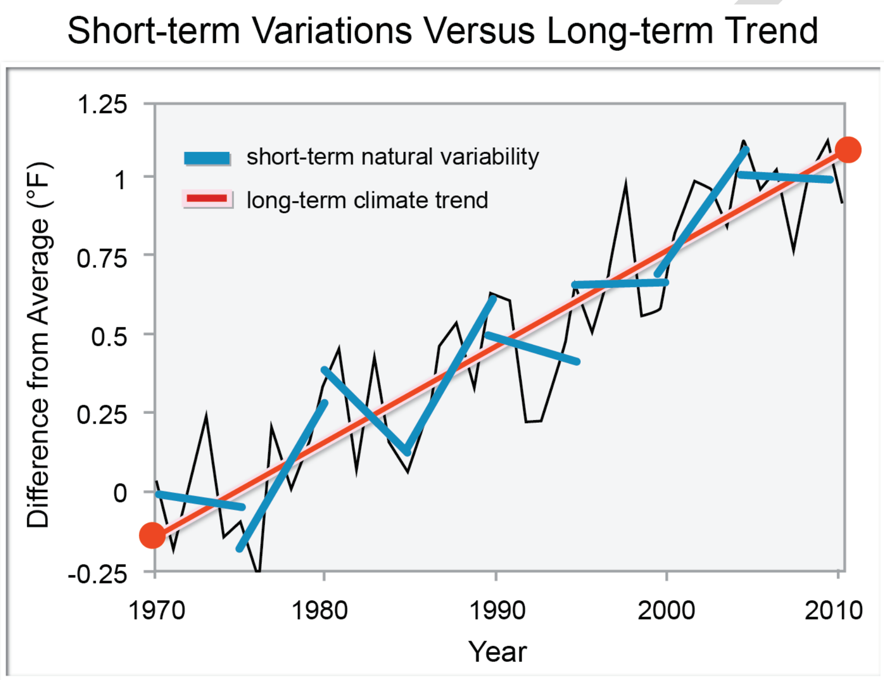

Figure 6: Short-term Variations Versus Long-term Trend

Caption: Short-term trends in global temperature (here, the blue lines that show temperature trends at five-year intervals from 1970 to 2010) can range from decreases to sharp increases. The evidence of climate change is based on long-term trends over 20-30 years or more (red line). Measurement data from NASA-GISS.

There is considerable decade-to-decade variability superimposed on the long-term trend. In most seasons and regions, the 1930s were relatively warm and the 1960s/1970s relatively cool. The most recent decade of the 2000s was unusually warm. In fact, this decade was characterized by the warmest winter everywhere except the Southeast, the warmest spring everywhere, the warmest summer in the Northwest and Southwest, and the warmest summer everywhere except the Southwest. On an annual basis, the 2000s were the warmest everywhere.

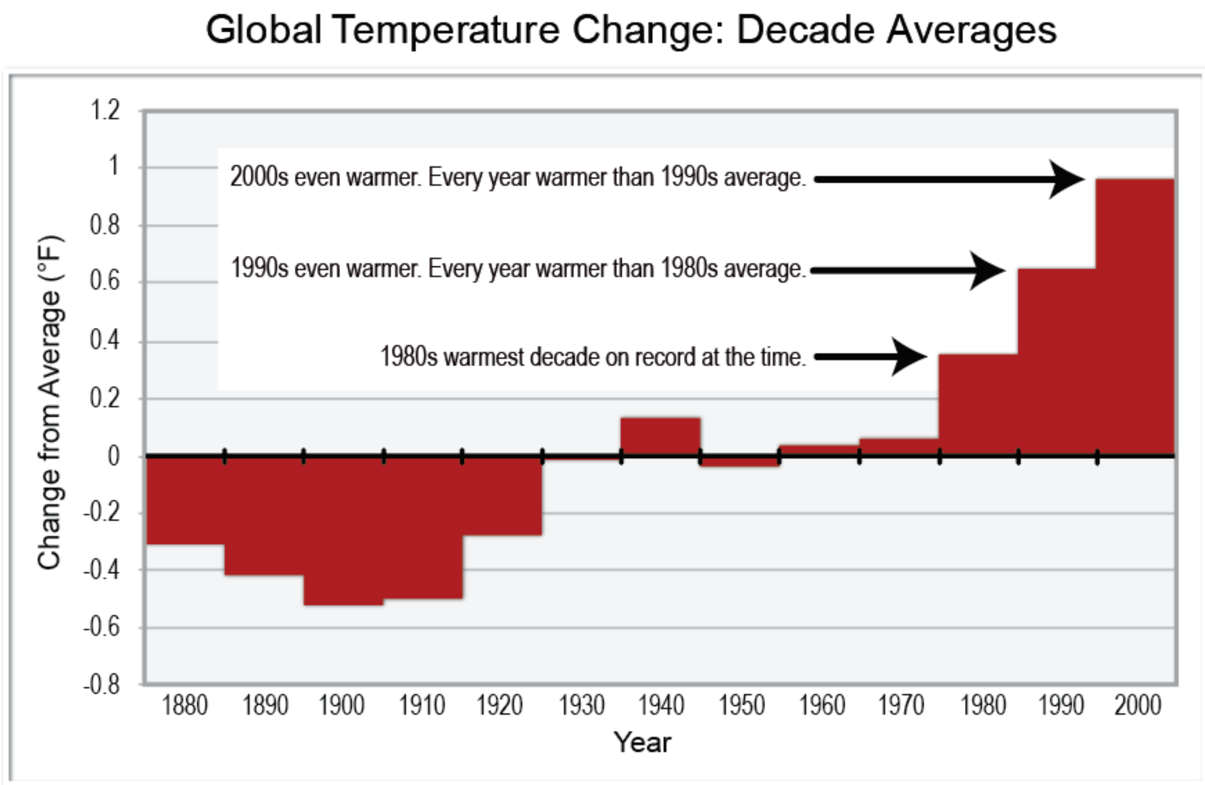

Figure 7: Global Temperature Change: Decade Averages

Caption: The last five decades have seen a progressive warming of the Earth. (From The State of the Climate 2009).

E. Is it getting warmer at the same rate everywhere? Are these trends likely to continue?

Many scientists do not like the term "global warming" that has been popularly used to describe climate change, because it might imply that it is warming everywhere, which is not the case. Temperature changes in a given location are a function of multiple factors, from global to local and including both human and natural influences. In some parts of the world, including the southeastern U.S. and the North Atlantic region, temperatures actually fell over the last century. At smaller spatial scales, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale.

Many scientists prefer the term "climate change," which connotes a much larger picture: broad changes in what are considered "normal" conditions. This definition encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of severe weather events, and other features of the climate system.

At the global scale, it is virtually certain that some future years will be cooler than the preceding year and likely that some decadal periods will be cooler than the preceding decade. Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future. Nonetheless, each successive decade in the last 50 years has been the warmest on record, and the period from 2000 to 2010 was the warmest decade in at least the last 2,000 years. It is virtually certain that future global temperatures averaged over climate timescales of 30 years or more will be higher than preceding periods, and that global temperature will continue to increase throughout the remainder of this century as a result of heat-trapping gas emissions that have already been emitted from human activities, as well as future emissions. Regional and local temperatures exhibit greater variability than global temperatures, but even at a particular location, warming becomes increasingly likely as the timeframe lengthens.

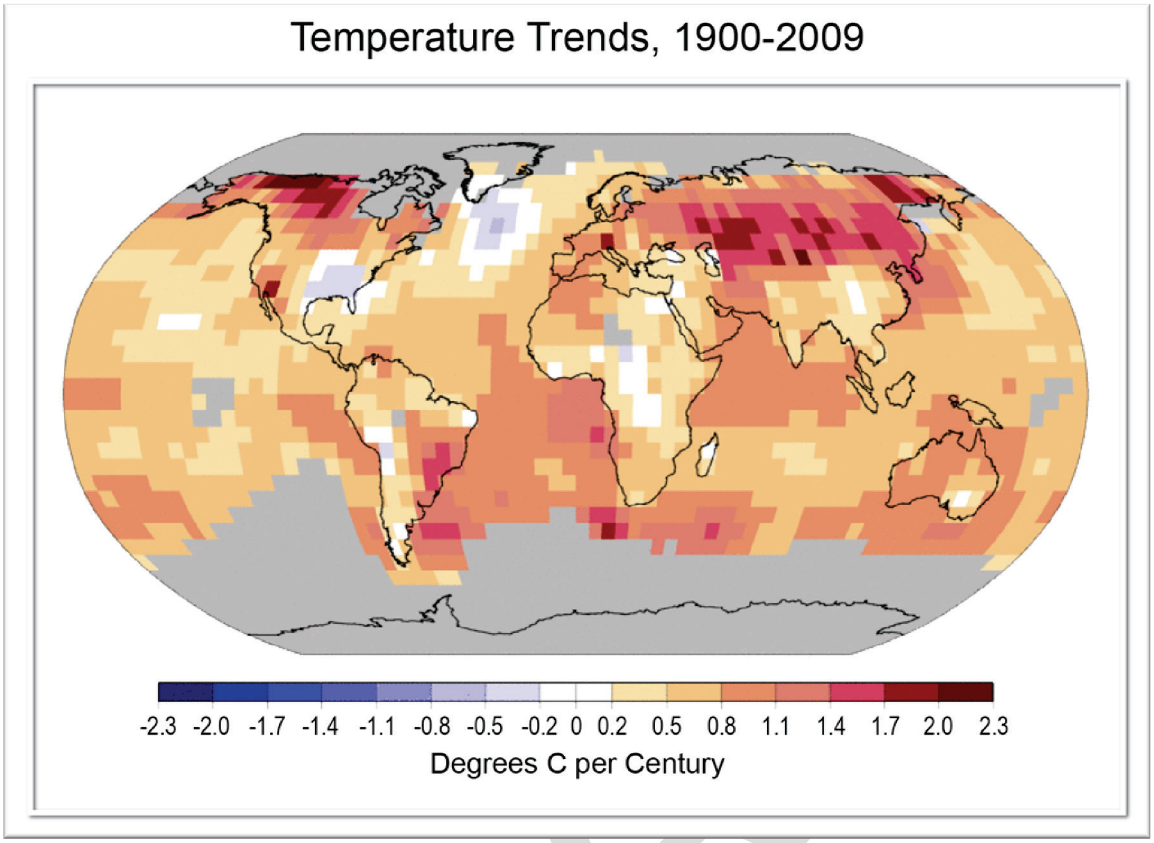

Figure 8: Temperature Trends, 1900-2009

Caption: Observed trend in temperature from 1900 to 2009; yellow to red indicates warming, while blue indicates cooling. There are substantial regional variations in trends across the planet. For example, for the U.S., annual, winter, and spring temperatures are rising. In the summer, temperatures are rising in the Northwest, Southwest, and Northeast, but not in the Southeast, Midwest, and southern Great Plains. The lack of warming in the Southeast and in the Midwest and Great Plains summers is unusual in a global context, and has been dubbed the "warming hole." These patterns exist because global circulation patterns transmit water and energy from the oceans across the land through a number of complicated mechanisms, such as the "jet stream" that moves from west to east in patterns that have been relatively consistent and predictable over time. Some of these mechanisms are now shifting in response to increased warming of the oceans and the atmosphere. Source: NOAA NCDC.

Regional Time Series of Decadal Average Temperature Change

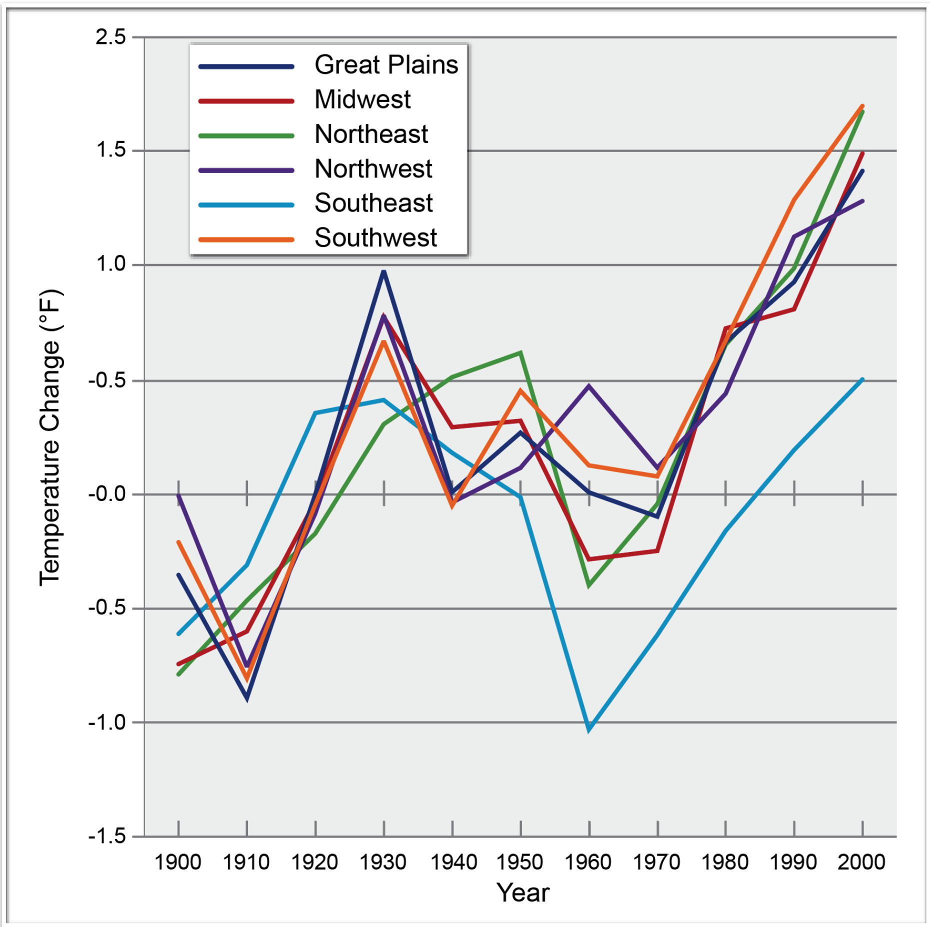

Figure 9: Regional Time Series of Decadal Average Temperature Change

Caption: Time series of decadal-averaged annual temperature (°F) for the six regions of the contiguous U.S. (Figure source: NOAA NCDC / CICS-NC)

F. How long have scientists been investigating human influences on climate?

The scientific basis for understanding how heat-trapping gases can affect the Earth's climate dates back to the French scientist and philosopher Joseph Fourier, who established the existence of the natural greenhouse effect in 1824. The heat-trapping abilities of greenhouse gases were corroborated by Irish scientist John Tyndall with experiments beginning in 1859.

The greenhouse effect is the result of heat-trapping gases, such as water vapor, carbon dioxide, and methane, in the Earth's atmosphere. These gases are virtually transparent to the Sun's energy, allowing nearly all of it to reach the Earth's surface. However, they are relatively opaque to the heat energy the Earth radiates back outward, trapping some of it inside the atmosphere and preventing it from escaping to space. Some of the trapped energy is re-radiated back down to the Earth's surface. This natural trapping effect makes the average temperature of the Earth nearly 60°F warmer than what it would be otherwise.

By the late 1800s, scientists were aware that burning coal, oil, or natural gas produced carbon dioxide, a key heat-trapping gas. They were also aware that methane, another heat-trapping gas, was released during coal mining and other human activities. And they knew that, since the Industrial Revolution, humans were producing increasing amounts of these gases. It was clear that humans were increasing the natural greenhouse effect and that this would warm the planet.

In 1890, Svante Arrhenius, a Swedish chemist, calculated the effect of increasing fossil fuel use on global temperature. This climate model, computed by hand, took two years to complete. Arrhenius' results were amazingly (and somewhat serendipitously) similar to those produced by the most up-to-date global climate models today, although he did not anticipate that atmospheric levels of carbon dioxide would increase as quickly as they have.

In 1938, a British engineer, Guy Callendar, connected rising carbon dioxide levels to the observed increase in the Earth's temperature that had occurred to date. In 1958, Charles David Keeling began to measure atmospheric levels of carbon dioxide in the relatively unpolluted location of Mauna Loa on Hawai'i. Today, those data provide a clear record of the effect of human activities on the chemical composition of the global atmosphere.

Keeling's measurements maintain an accuracy and precision that allow scientists to separate fossil fuel emissions from natural sources, validating the work of scientists stretching back nearly two hundred years. Today, many more sources of data corroborate the work of these early pioneers in the field of climate science.

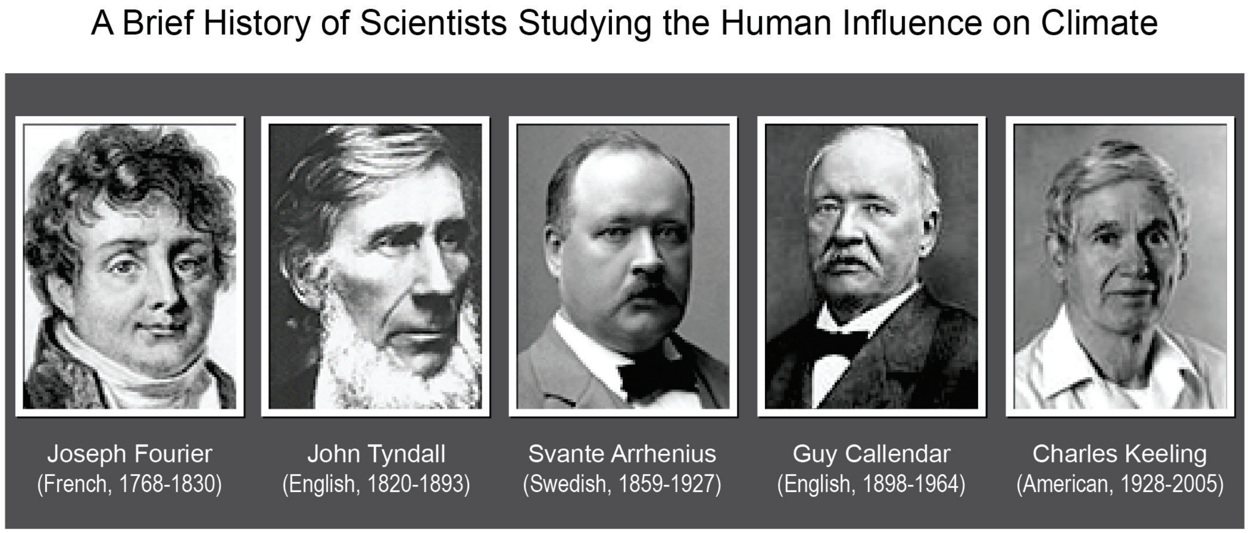

Figure 10: A Brief History of Scientists Studying the Human Influence on Climate

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

Before the Industrial Revolution, natural levels of carbon dioxide in the atmosphere averaged around 280 parts per million (ppm). In other words, carbon dioxide made up about 0.028% of the volume of the atmosphere. Methane and nitrous oxide, other heat-trapping gases, made up even less, about 700 parts per billion (ppb) and 270 ppb, respectively. Over the last few centuries, emissions from human activities have increased carbon dioxide levels to more than 390 ppm. Over the same time period, methane and nitrous oxide levels in the atmosphere rose to around 1800 ppb (parts per billion) and 320 ppb, respectively.

How could gases that make up such a small proportion of the atmosphere affect global climate? First, the amount of carbon dioxide contained in the atmosphere is more than 3,000 billion tons. That is the equivalent of over 16 billion blue whales, the largest known animal on Earth; not such a small amount after all. Second, we all know it's not the amount of a substance that matters, but the potency. A small amount of medicine can cure a disease; an amount of bacteria so small that they are invisible to the human eye can make us very sick.

The reason why heat-trapping gases like carbon dioxide, methane, and nitrous oxide have such an influence on Earth's climate is that they are transparent to visible and ultraviolet solar energy but are very strong absorbers of infrared heat energy. Water vapor is the most important naturally occurring heat-trapping greenhouse gas, but the amount of water vapor in the atmosphere tends to increase as the atmosphere warms – as a result, water vapor is considered a "feedback" rather than a direct forcing on climate.

Increases in atmospheric levels of heat-trapping gases like carbon dioxide, methane, and nitrous oxide, all of which are increasing because of human activities, enable these gases to absorb ever-increasing amounts of infrared heat energy. The gases absorb the infrared energy emitted from the Earth's surface and then radiate some of this heat back to the surface, effectively trapping the heat inside the Earth's climate system and warming the Earth's surface.

These heat-trapping gases do not absorb energy equally across the infrared spectrum. Carbon dioxide absorption is very strong at certain wavelengths of infrared radiation, whereas water vapor absorbs more broadly across most of the spectrum. Small increases in heat energy absorption by carbon dioxide and other heat-trapping gases can trigger increases in water vapor that amplify the infrared trapping, leading to further warming.

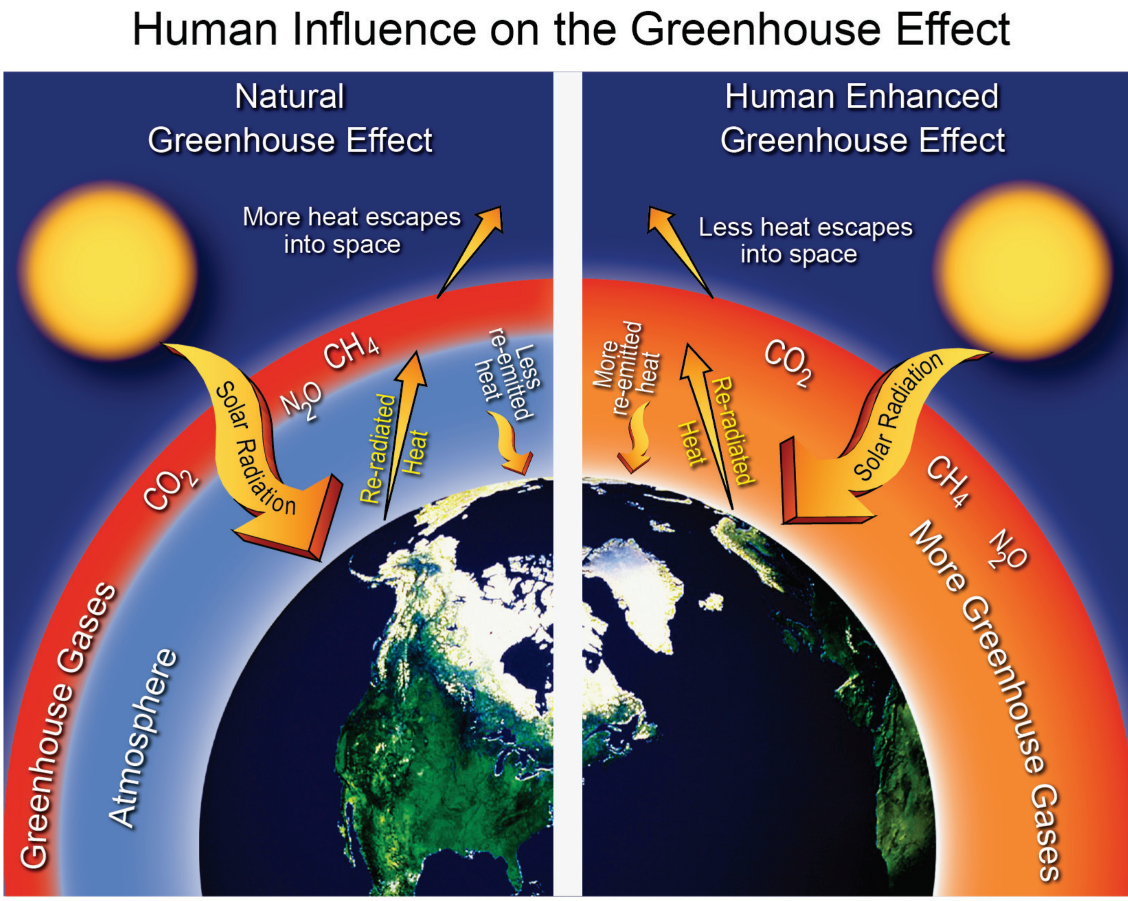

Figure 11: Human Influence on the Greenhouse Effect

Caption: Left: Naturally occurring heat-trapping gases, including water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), normally trap some of the Sun's heat, keeping the planet inhabitable as we know it. **Right**: Human activities, such as the burning of fossil fuels, are increasing levels of CO_2 and other heat-trapping gases, leading to an enhanced greenhouse effect. The result is global warming and unprecedented rates of climate change. (Figure source: National Park Service)

H. Could the Sun or other natural factors explain recent climate changes?

Changes in energy from the Sun are an important driver of the Earth's climate. Past proxy data (from ice cores, tree rings, and other evidence) reveal a generally good correlation between global temperature and changes in solar output. Over the last 50 years, however, temperature change cannot be explained by changes in the energy from the Sun. Since accurate satellite-based measurements of solar radiation began in 1978, the Sun's output has slightly decreased, which should result in slightly lower temperatures; but the Earth's temperature has continued to warm. All told, the Sun can explain less than 10% of the increase in temperature since 1750, and none of the increase in temperature since 1960.

Patterns of vertical temperature change (from the Earth's surface to the upper atmosphere) provide definitive evidence that the Sun cannot be responsible for the observed changes in climate. An increase in solar output would warm the atmosphere consistently from top to bottom. Warming from increasing heat-trapping gases, on the other hand, should be concentrated in the lower atmosphere. At the same time, heat-trapping gas-related warming would cool the upper atmosphere by reducing the amount of the Earth's infrared heat energy that reached it. This is exactly the pattern that has been observed. Satellite measurements and weather balloon records reveal that the troposphere has warmed and the stratosphere has cooled.

Large explosive volcanic eruptions can also cool climate for a few years after the eruption. In the atmosphere, sulfur dioxide from volcanoes is converted into sulfuric acid particles that can scatter sunlight, cooling the Earth's surface. Particles from exceptionally large eruptions like Pinatubo in 1991 or Krakatoa in 1883 can penetrate well into the stratosphere, where they can stay for several years. Eventually, they fall back into the troposphere where they are rapidly removed by precipitation. Volcanoes also emit carbon dioxide, but this amount is less than 1% annually of the emissions occurring from human activities.

Natural factors cannot explain recent warming. In fact, if global temperature over the last 50 years were controlled by natural factors such as the Sun, it should have gotten cooler. Instead, it has warmed significantly.

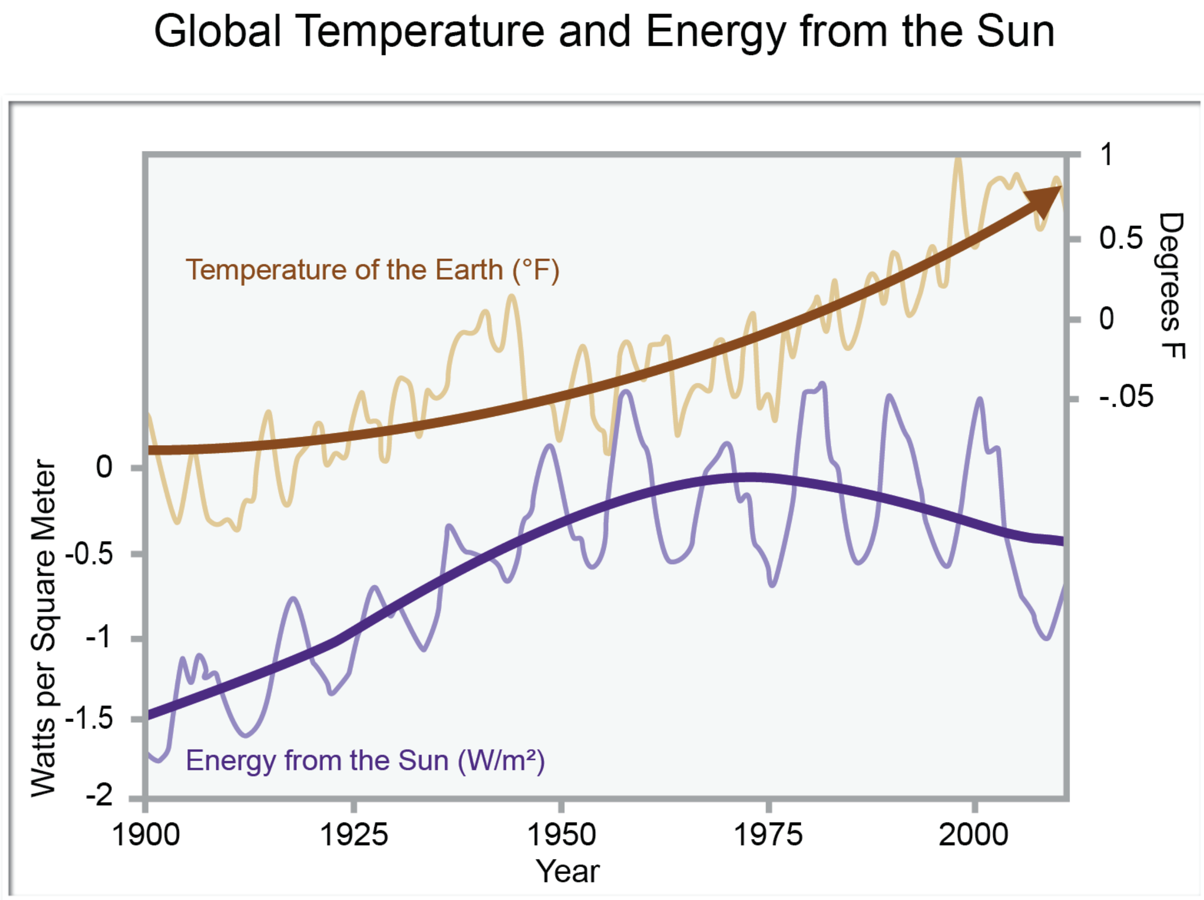

Figure 12: Global Temperature and Energy from the Sun

Caption: Changes in the global surface temperature and the solar flux since 1900 (relative to 1961-1990). The temperatures are based on observations, while the solar flux is based on satellite observations starting in 1978 and on proxy observations before then. The temperature data are from NASA GISS, and the TSI data (from 1880-1978) are from Krivova et al, (2007) and (from 1979-2010) PMOD.

I. How do we know that human activities are the primary cause of recent climate change?

Scientists are continually designing experiments to test whether observed climate changes are unusual and what the causes of these changes may be. This field of study is known as "detection and attribution." Detection is simply looking for evidence of unusual changes or trends. Attribution attempts to identify the causes of these changes from a line-up of "prime suspects" that include changes in energy from the Sun, powerful volcanic eruptions, or human emissions of heat-trapping gases.

Such studies have clearly shown that human activities are primarily responsible for recent climate changes. Detection and attribution analyses have confirmed that a wide variety of recent changes (see CAQs C and H) cannot have been caused either by internal climate system variations or by solar and volcanic influences alone. Human influences on the climate system – including heat-trapping gas emissions, atmospheric particulates, land-use and land-cover change – are required to explain recent changes.

Detection and attribution has been used to quantify the contribution of human influences to changes in global average conditions, in extreme events, and even in the risk of specific types of events, such as the 2003 European heat wave. Such analyses have found it impossible to explain observed changes in many aspects of the climate system without including the influences of human activities on climate. Scientific analyses also provide extensive evidence that the likelihood of some types of extreme events (such as heavy rains, heat waves, and strong hurricanes) is now significantly higher due to human-induced climate change.

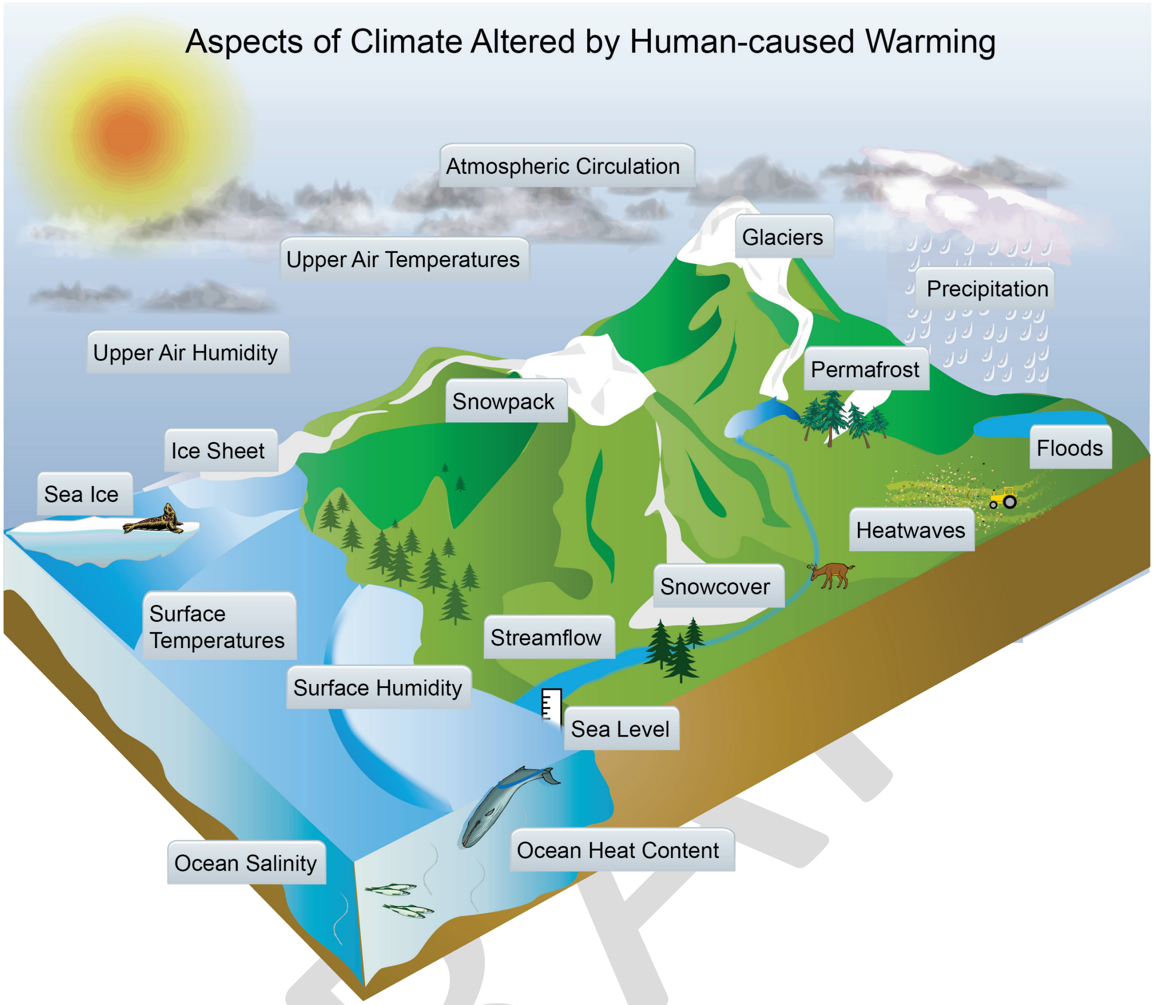

Figure 13: Aspects of Climate Altered by Human-caused Warming

Caption: Figure shows some parts of the climate system in which changes have been attributed to human activities. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be accounted for without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the single most significant contributor to recently observed climate changes. (Figure source: NOAA NCDC)

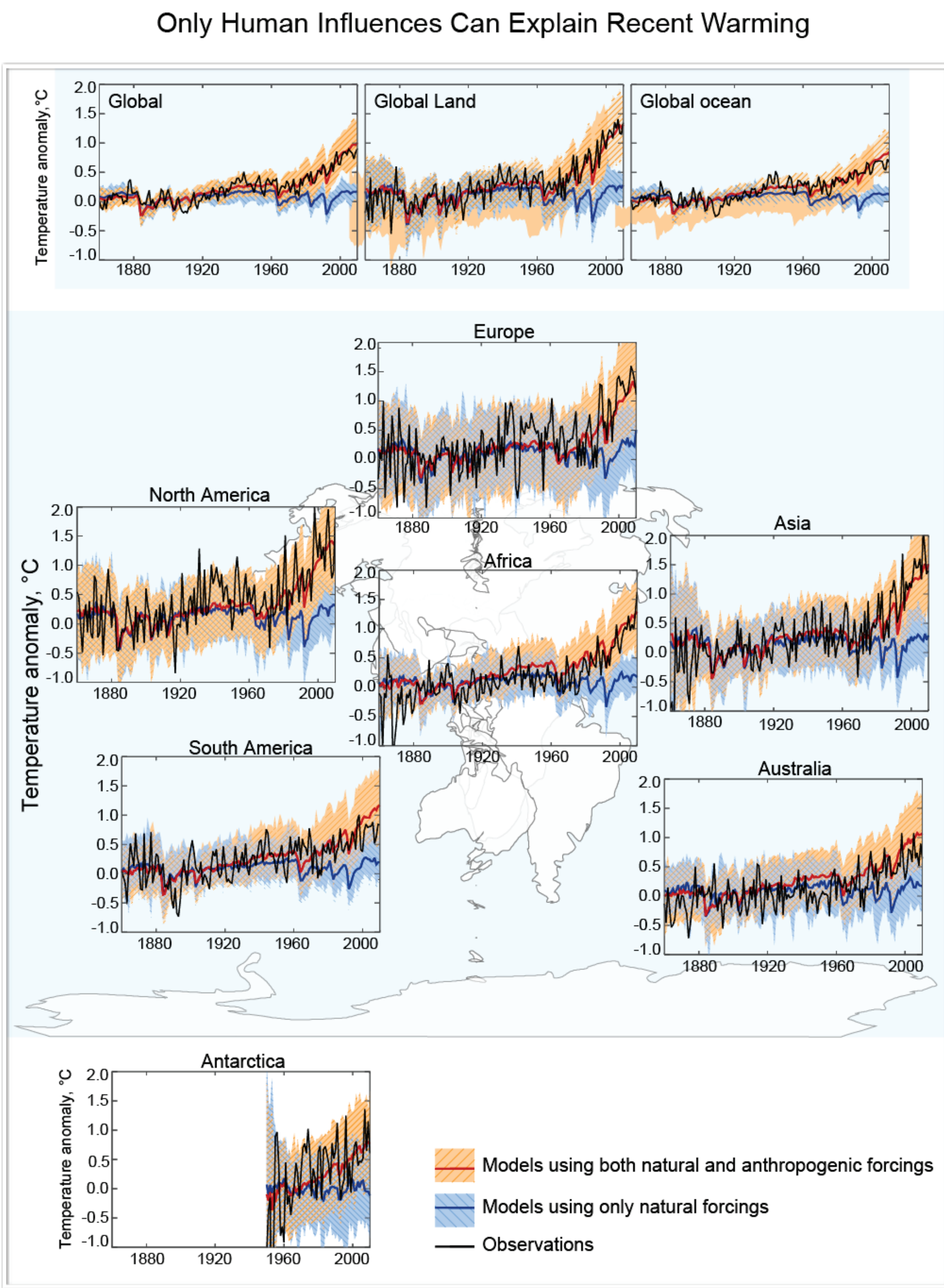

Figure 14: Only Human Influences Can Explain Recent Warming

Caption: Detection and attribution of surface air temperature changes at continental and global scales. The black line depicts the observed changes in ten-year averages. The blue shading represents estimates from a broad range of climate simulations including solely natural (solar and volcanic) changes in forcing. The pink shading adds in the effects of including human contributions. It is impossible to explain the observed changes both globally and on a continent-by-continent basis without including the influence of human activities on climate. (Source: Jones et al. submitted)

J. What is and is not debated among climate scientists about climate change?

The scientific method is built on scrutiny and debate among scientists. Scientists are rigorously trained to conduct experiments to test a question, or hypothesis, and submit their findings to the scrutiny of other experts in their field. Part of that scrutiny, known as "peer review," includes independent scientists examining the data, analysis methods, and findings of a study that has been submitted for publication. This peer review process provides quality assurance for scientific results, ensuring that anything published in a scientific journal has been reviewed and approved by other independent experts in the field, and that the authors of the original study have adequately responded to any criticisms or questions they received. However, peer review is only the first step in the long process of acceptance of new ideas. After publication, other scientists will often undertake other studies that may support or reject the findings of the original study. Only after an exhaustive series of studies over many years, by many different research groups, are new ideas widely accepted.

Given the fact that science is built on the premise of criticism rather than consensus, the widespread agreement in the scientific community regarding the reality of climate change and the leading role of human activities in driving this change is nothing short of remarkable. More than 97% of scientists in this field agree that the world is unequivocally warming and that human activity is the primary cause of the warming experienced over the past 50 years.

This conclusion is based on multiple lines of evidence, from basic physics to the patterns of change through the climate system (including the atmosphere, oceans, land, biosphere, and cryosphere). The warming of global climate and its causes are not matters of opinion; they are matters of scientific evidence, and that evidence is clear. Scientists do not "believe" in human-induced climate change; rather, the widespread agreement among scientists is based on the vast array of evidence that has accumulated over the last 200 years. When all of the evidence is considered, the conclusions are clear.

This does not mean we have perfect understanding of climate change. Spirited debates on some details of climate science continue. These debates focus on questions such as: Exactly how sensitive is the Earth's climate to human emissions of heat-trapping gases? How will climate change affect clouds? How do particle and soot emissions affect clouds? How will climate change be affected by changes in clouds and the oceans? All these questions and more serve as healthy indicators that the scientific method is alive and well in the field of climate science. But the primary role of human activities in driving recent change is not in dispute (see CAQ I).

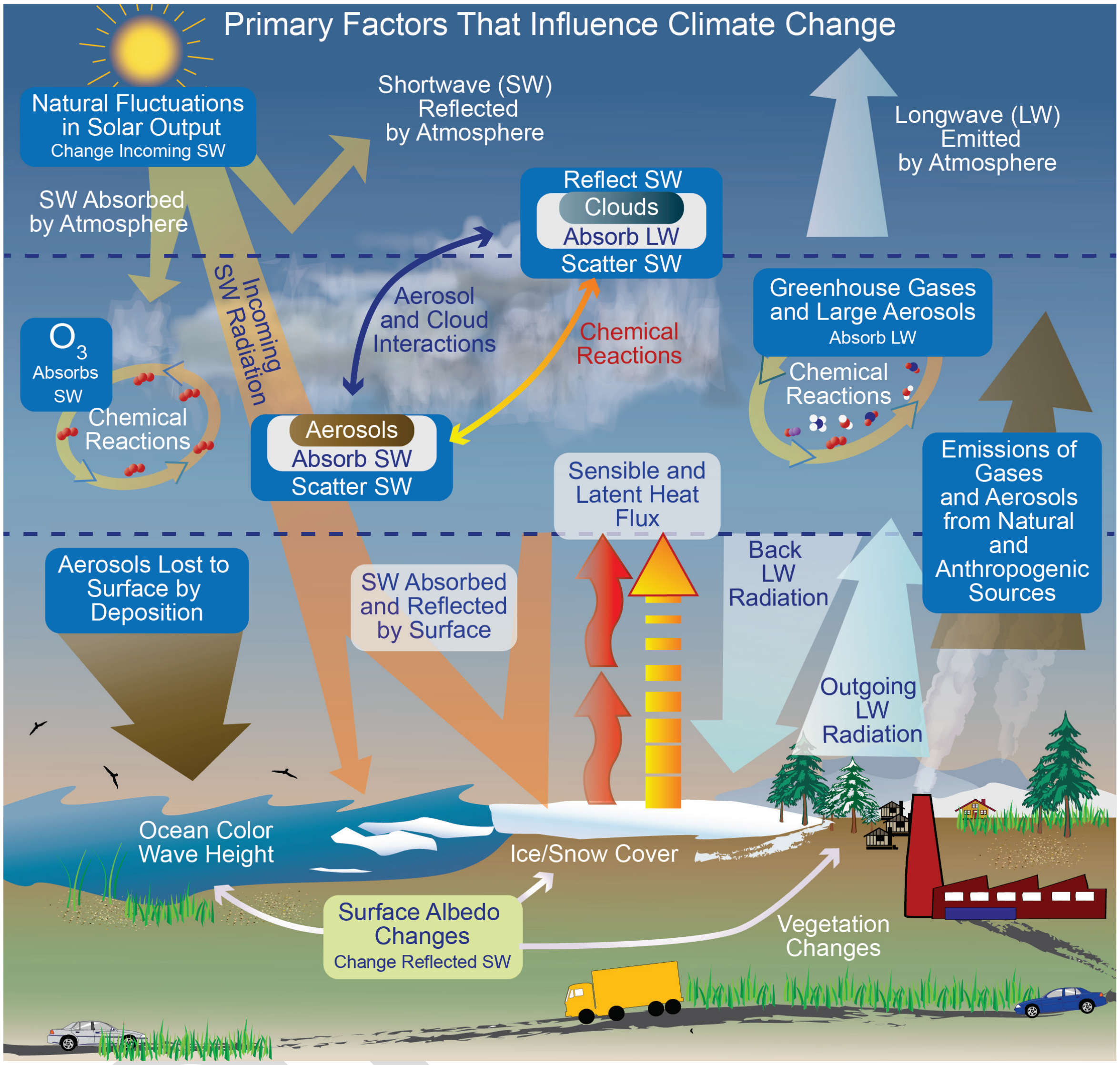

Figure 15: Primary Factors That Influence Climate Change

Caption: Main drivers of climate change. The energy balance between incoming solar short wave (SW) radiation and outgoing long wave (LW) radiation is influenced by global climate "drivers." Natural fluctuations in solar output (solar cycles) can cause changes in the amount of incoming SW radiation. Human activity changes the emissions of gases and particles, which are involved in atmospheric chemical reactions, resulting in modified ozone and aerosol amounts. Ozone and aerosols scatter and reflect SWR, changing the energy balance. Some aerosol particles act as cloud condensation nuclei, modifying the properties of cloud droplets. Because clouds interact strongly with both SW and LW radiation, small changes in the properties of clouds have important implications for the radiative budget. Human-caused changes in the concentrations of heat-trapping gases and large particles in the atmosphere modify the LWR portion of the energy balance by absorbing more outgoing LWR and reemitting less energy from altitudes having a lower temperature. The albedo (reflectivity) of the surface varies over time and by location with changes in vegetation or land surface cover, snow or ice cover, and ocean color. These changes are driven both by naturally occurring seasonal and diurnal changes (for example, changes in snow cover from winter to summer), as well as human influences (for example, changes in vegetation height). (Need Source)

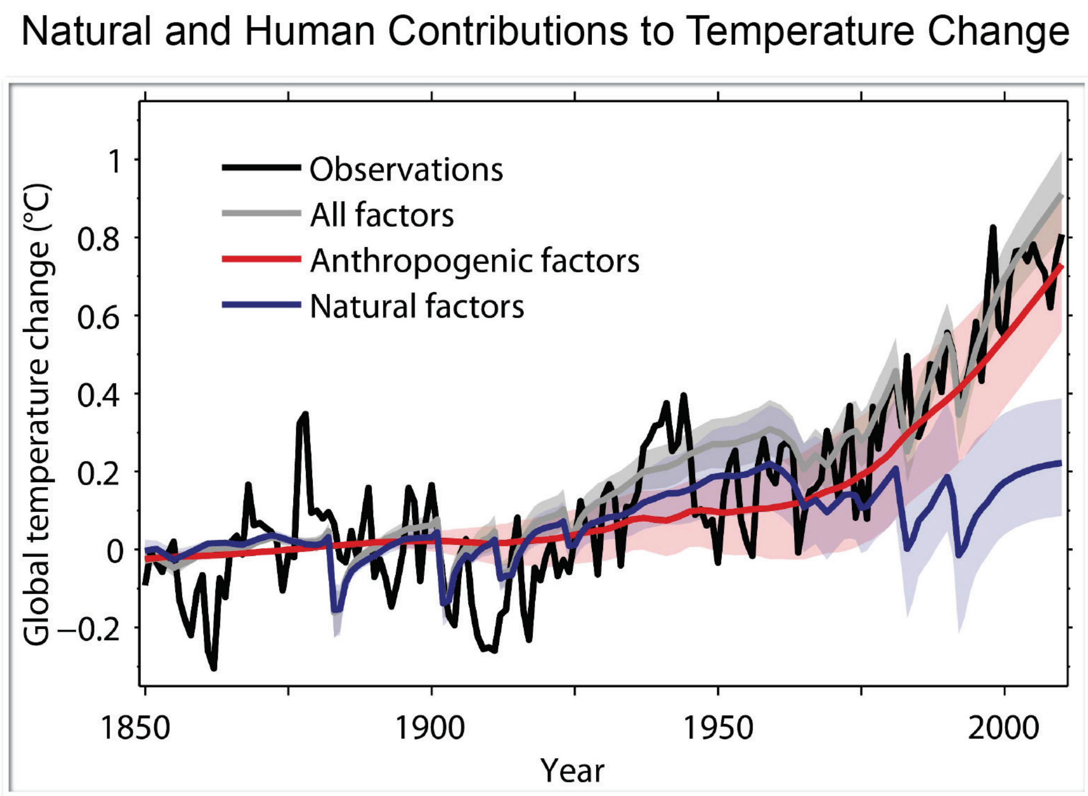

Figure 16: Natural and Human Contributions to Temperature Change

Caption: Relative contributions to global temperature changes since 1850. Black line represents observed temperatures. Blue line indicates the modeled contribution of natural factors to global temperatures. The red line indicates the contribution of human-caused factors. The gray line represents the combined total of natural and human-caused factors. The human-caused contribution dominates the temperature increase in recent decades. (Source: adapted from Huber and Knutti, 2011)

K. Is the global surface temperature record good enough to determine whether climate is changing?

Global surface temperatures are measured by weather stations over land, and by ships and buoys over the ocean. These records extend back regionally for over 300 years in some locations and near-globally to the late 1800s.

Scientists have undertaken painstaking efforts to obtain, digitize, and collate these records. Because of the way these measurements have been taken, many of the records contain extraneous effects caused by, for example, a change of instrument or a station move. It's essential to carefully examine the data to identify and adjust for such effects before the data can be used to estimate any change in climate.

A number of different research teams have taken up this challenge. Some have spent decades carefully analyzing the data and continuously reassessing their approaches. These independently produced estimates are in very good agreement at both global and regional scales.

Scientists have also considered other influences that could contaminate temperature records. For example, many thermometers are located in urban areas that could have warmed over time due to the urban heat island effect (in which heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside). At least three different research teams have examined how this might affect U.S. temperature trends. All have found that this effect is adequately accounted for by the data corrections. If all of the urban stations are removed from the global temperature record, the global warming of the past 50 years is still apparent. Other studies have shown that the warming (or cooling) trends of rural and urban areas in close proximity essentially match, even though the urban areas may have higher temperatures overall.

There have been a number of studies that have examined the U.S. and global temperature records in great detail. These have used different ways to study the effects of instrument changes, observations changes, site moves, and other sources of error. All studies reinforce high confidence in the reality of the observed upward trends in temperature.

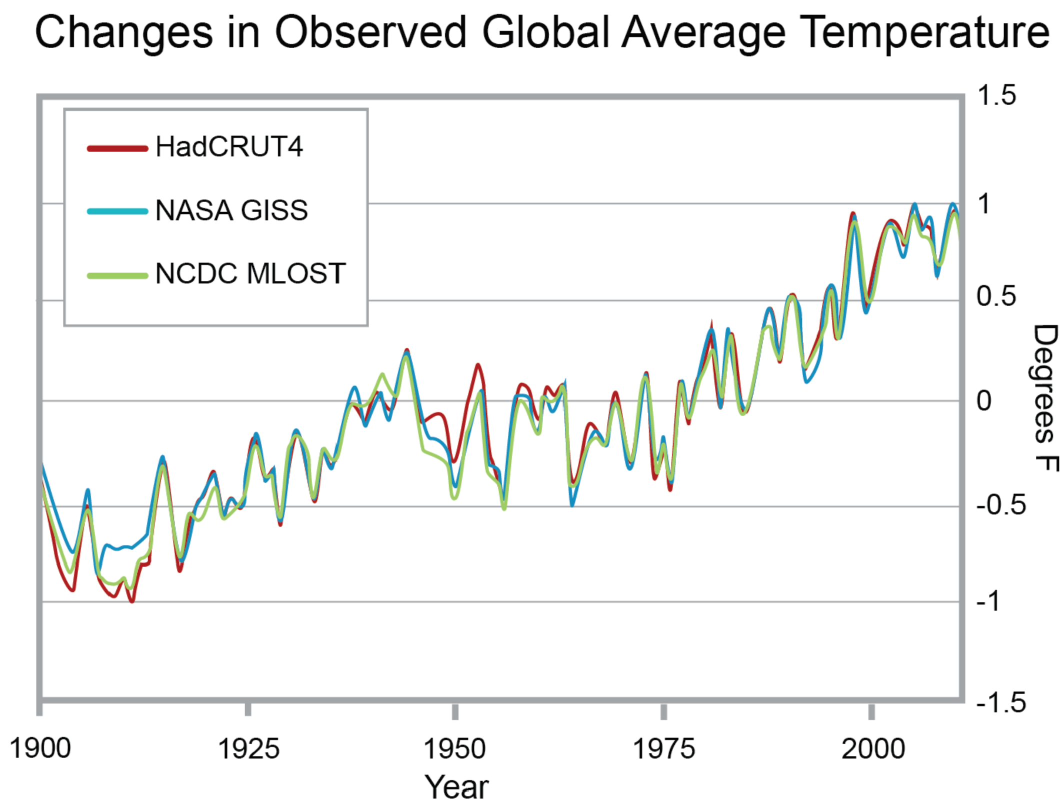

Figure 17: Changes in Observed Global Average Temperature

Caption: Temperature time series from three global surface records on land and oceans. Thin lines show annual differences in temperature relative to the 1961-1990 average. Differences between datasets arise from different choices in data selection, analysis, and averaging to form a global mean. These differences are small and do not affect the conclusion that the global surface temperatures are increasing. (Need Source)

L. Is Antarctica gaining or losing ice? What about Greenland?

The Antarctic region is characterized by two distinct types of ice: the ice sheet overlying the Antarctic continent itself, and the sea ice that lies on top of the Southern Ocean surrounding the Antarctic continent. Antarctic sea ice cover expands seasonally, covering about 5.8 million square miles at the end of winter and shrinking to about 0.8 million square miles at the end of summer. Because sea ice is simply frozen seawater at the top of the ocean, it does not affect global sea level. Since continuous satellite coverage began in the 1970s, Arctic summer sea ice has decreased substantially, but there has been little trend in Antarctic summer sea ice, in part because it already disappears around much of the continent.

The Antarctic ice sheet, consisting of a thick glacial ice (up to 3 miles deep) that was originally deposited as snow, is a different story. The amount of water locked up in the present-day Antarctic ice sheet is enough to raise sea level about 200 feet. Because Antarctica is so cold, there is little melt of the ice sheet in the summer. However, the ice on the continent slowly flows down the mountains and through the valleys toward the ocean. Some parts of the ice sheet extend out into the ocean as "ice shelves." Here, above-freezing ocean water speeds up the process called "calving" that breaks the ice into free floating icebergs.

There is evidence that melting and calving and the flow of ice into the oceans around Antarctica has accelerated in recent decades and is now contributing about 0.005 to 0.010 inches per year to sea level rise. There is concern that the West Antarctic Ice Sheet, which sits partly below sea level and contains enough ice to raise global sea levels by 10 feet, could begin to lose ice much more quickly if ice shelves in the region begin to disintegrate at the edges.

Greenland contains only about one tenth as much ice as the Antarctic ice sheet, but if Greenland's ice were to entirely melt, global sea level would rise 23 feet. (In Antarctica, only the melting of the West Antarctic ice sheet is considered plausible in the next few centuries.) Greenland is warmer than Antarctica and in a region where air and ocean temperatures are rising. Unlike Antarctica, melting occurs over large parts of the surface of Greenland's ice sheet each summer. Greenland's melt area has increased over the past several decades. Satellite measurements indicate that the Greenland ice sheet is presently thinning at the edges (especially in the south) and slowly thickening in the interior, increasing the steepness of the ice sheet, which causes the ice to flow toward the ocean. Several of the major outlet glaciers that drain the Greenland ice sheet have sped up in the past decade. Recent scientific studies suggest that warming of the ocean at the edges of the outlet glaciers may contribute to this speed-up. Regardless of the mechanism, it appears that Greenland's ice loss has increased substantially in the past decade or two, and is now 0.01 to 0.02 inches per year (about twice the rate of Antarctica's mass loss). This increased rate of ice loss means that Greenland's contribution to global sea level rise is now similar to the effect from smaller glaciers worldwide and from Antarctica.

Together, ice sheet melt from Greenland and Antarctica represents the largest uncertainty in projections of future sea level rise.

Evaluating Ice Loss

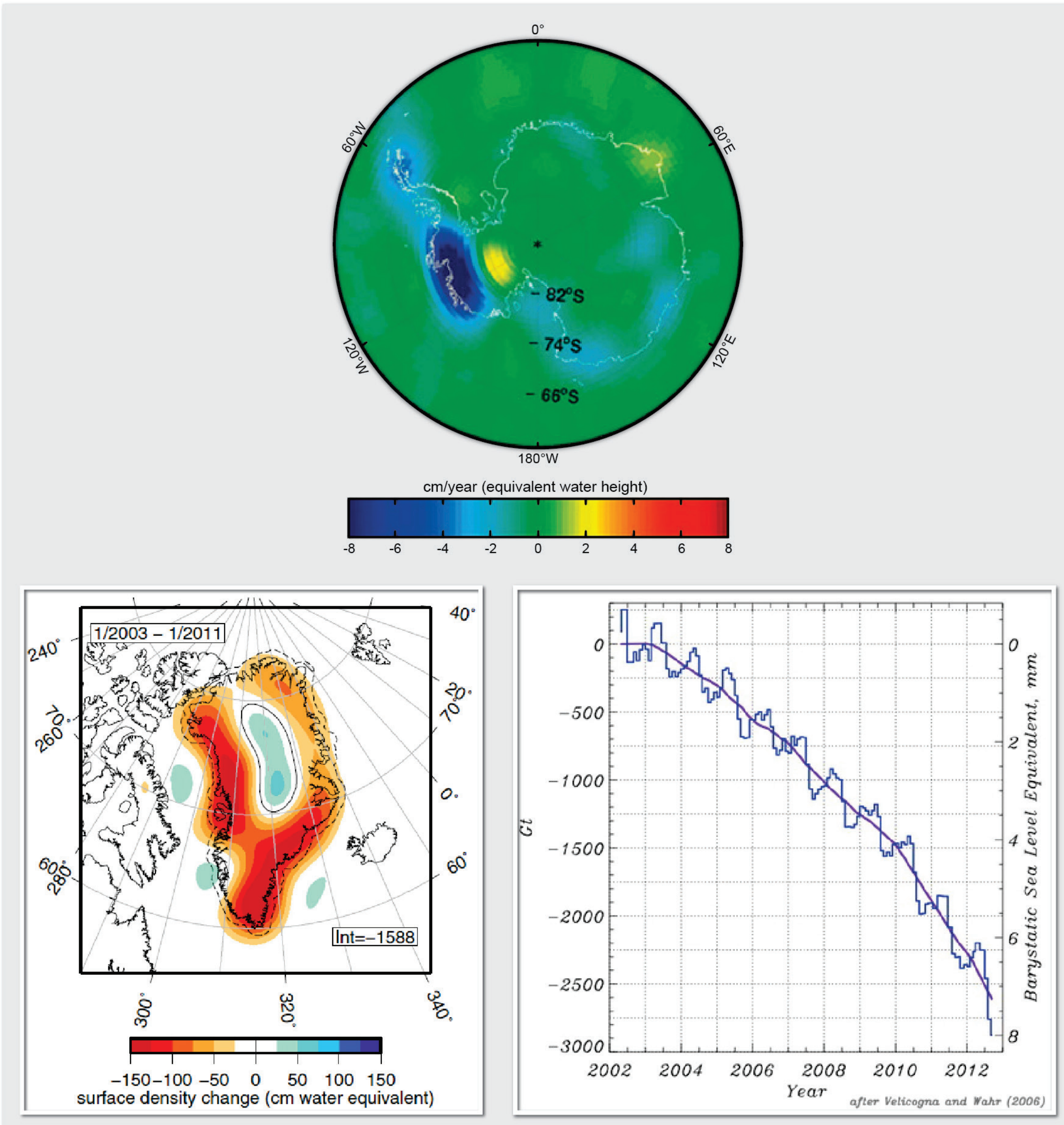

Figure 18: Evaluating Ice Loss

Caption: Scientists can evaluate ice loss by observing changes in the gravitational fields over Greenland and Antarctica. Fluctuations in the pull of gravity over these major ice sheets reflect the loss of ice over time. Over the last decade, the GRACE (Gravity Recovery and Climate Experiment) satellites have measured changes in the gravitational pull of the continents that show where the ice sheets are losing mass to the oceans. The blue regions in the figures show where the ice is getting thinner. The GRACE satellites have proven that on the whole, both Greenland and Antarctica are losing ice as the atmosphere and oceans warm. Source: top: NASA; bottom left, Harig and Simons (2012); bottom right, NOAA 2012 adapted from Velicogna and Wahr (2006). (Need Source)

M. What about global cooling predictions in the 1970s?

An enduring myth about climate science is that in the 1970s the climate science community was predicting "global cooling" and an "imminent" ice age. A review of the scientific literature suggests that this was not the case. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Where did all the discussion about global cooling come from? First, temperature records from about 1940 to 1970 show a slight global cooling trend, intensified by temporary increases in snow and ice cover across the Northern Hemisphere. Unusually severe winters in Asia and parts of North America in 1972 and 1973 raised people's concerns about cold weather. The popular press, including *Time*, *Newsweek*, and *The New York Times*, carried a number of articles about the cooling climate at that time.

Second, climate scientists study both natural and human-induced changes in climate. Over the last century, scientists have continued to try to understand when and why the Earth slipped into and out of ice ages. Confirmation of what are called the Milankovitch cycles (cyclical changes in the Earth's orbit that explain the onset and ending of ice ages) led a few scientists in the 1970s to suggest that the current warm interglacial period might be ending soon, plunging the Earth into a new ice age over the next few centuries. Scientists continue to study this issue today; the latest information suggests that, if the Earth's climate were being controlled primarily by natural factors, the next glaciation would begin sometime in the next 1,500 years. However, humans have so altered the composition of the atmosphere that the next glaciation has now been delayed indefinitely.

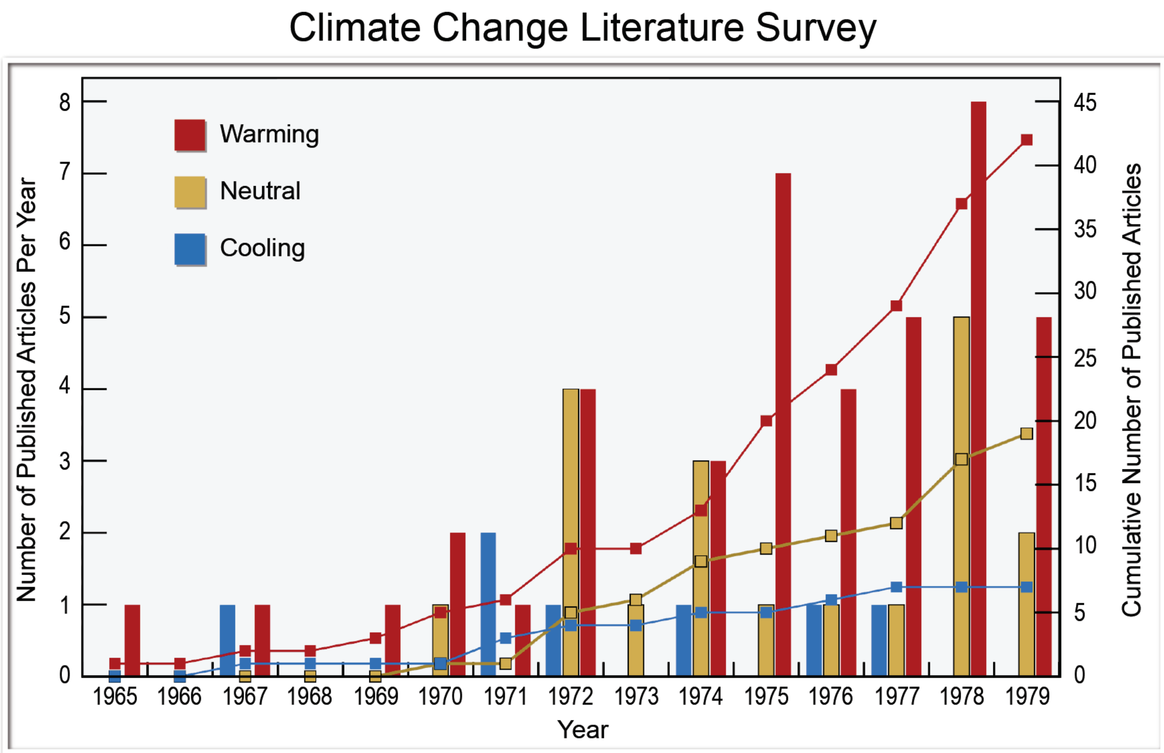

Figure 19: Climate Change Literature Survey

Caption: The number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories. For the period 1965 through 1979, the literature survey found seven papers suggesting further cooling, 20 neutral, and 44 warming. Based on Peterson et al. (2008).

N. How is climate projected to change in the future?

Future climate cannot be "predicted" because we cannot predict what society will choose to do with regard to emissions. Rather, climate can be projected given various assumptions regarding future human activities and the response of the climate system to those influences.

The relative importance of various sources of uncertainty changes over time. The uncertainties also depend on what type of change is being projected: whether in average conditions or extremes, or in temperature or precipitation, and so on. (see CAQ S).

Over the next few decades, global average temperature over 30-year climate timescales is expected to continue to increase (see CAQ D). The amount of climate change expected over this time period cannot be altered by reducing heat-trapping gas emissions or even by stabilizing atmospheric levels of carbon dioxide and other gases. This is because near-term warming will be caused primarily by emissions that have already occurred. There is a lag in the climate system's response to changes in atmospheric composition. This lag is primarily the result of the very large heat storage capacity of the world's oceans and the mixing time to the deep ocean. At smaller geographical scales, temperatures are projected to increase in most regions in the next few decades, but a few regions could experience temperature decreases – any climate change always represents the net effect of multiple global and local factors, both human-related and natural (see CAQ E).

Beyond the middle of this century, global and regional temperature will be determined primarily by the course of human emissions, as well as by the response of the Earth's climate system to those emissions. Efforts to rapidly and significantly reduce emissions of heat-trapping gases can still limit the global temperature increase to 3.6ºF (2ºC). However, significantly greater temperature increases are expected if emissions follow higher scenarios associated with continuing growth in the use of fossil fuels; in that case, the increase in global air temperatures could exceed 12ºF by the end of this century.

Precipitation patterns are also expected to continue change by the end of this century. In general, wet areas are projected to get wetter and dry areas, drier. In some areas, located in between wetter and drier areas, the total amount of precipitation falling over the course of a year is not expected to significantly change. Following the observed trends over recent decades, more precipitation is expected to fall as heavier precipitation events. In many mid-latitude regions, including the U.S., there will be fewer days with precipitation but the wettest days will be wetter.

Average U.S. Temperature Projections

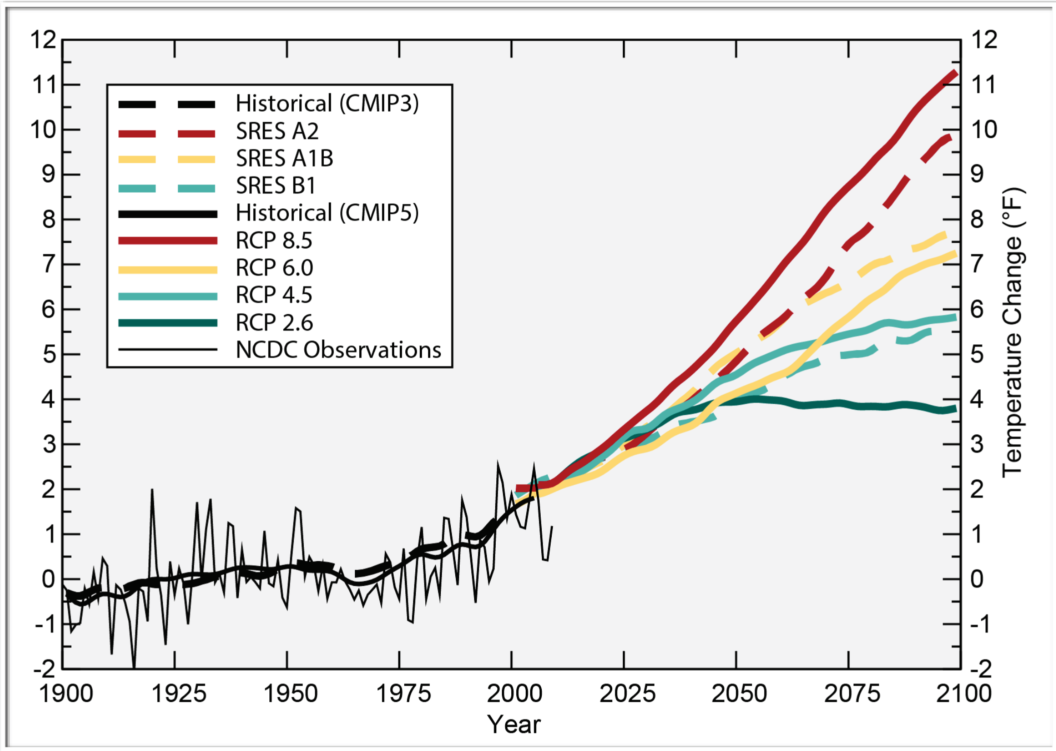

Figure 20: Average U.S. Temperature Projections

Caption: Projected average annual temperature changes (ºF) over the contiguous U.S. for multiple future emissions scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models. The solid lines are results from the most recent generation of climate models. Differences in these projections are principally a result of differences in the emissions scenarios. Source: CMIP3, CMIP5, NOAA, 2012.

O. Does climate change affect severe weather?

The harmful effects of severe weather raise concerns about how the risk of such events might be altered by climate change. An unusually warm month, a major flood or a drought, a series of intense rainstorms, an active tornado season, landfall of a major hurricane, a big snowstorm, or an unusually severe winter inevitably lead to questions about possible connections to climate change.

Climate change can and has altered the risk of some extreme events. For example, more extreme high temperatures and fewer extreme cold temperatures occur in a warmer climate (but extreme cold events can and do still occur). In the U.S., twice as many hot temperature records than cold records were broken in the decade of 2000-2010. Also, in many areas, floods and droughts are more likely as the climate changes. Climate change can alter atmospheric circulation and weather patterns, affecting the location and frequency of these and other extremes. However, for many extreme weather events important to the U.S., such as tornadoes, more research is needed to understand how climate change will affect them.

While there is always a chance that particular extreme events may have occurred naturally, from a statistical perspective, the likelihood of some of these events has clearly increased due to climate change.

The analogy of a baseball player who takes steroids may be useful in understanding how human and natural factors affect extreme weather. Without steroids, a very good baseball player will hit some home runs. Steroids will increase the likelihood of his doing so. While the effect will not be apparent each time the player bats, his long-term average performance will show a change. Similarly, with the “steroids” of heat-trapping gases added to the atmosphere, some types of extreme climate and weather events have become more frequent and/or intense due to climate change.

Blocking of Jet Stream

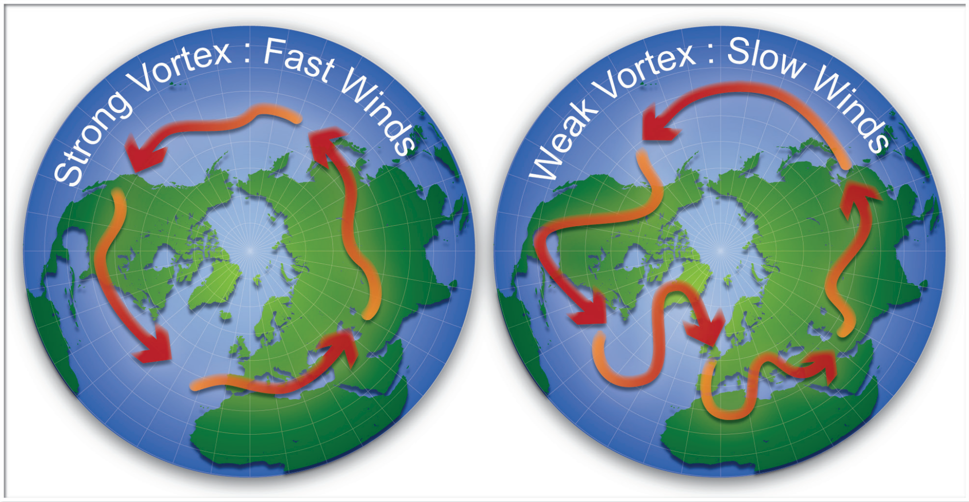

Figure 21: Blocking of Jet Streams

Caption: Examples of jet streams showing typical eastward flow (left) and a blocking pattern (right). The blocking pattern leads to persistent extremes of temperature and precipitation in different regions. Recent studies suggest that blocking may become more common if the present pattern of warming (greater in higher latitudes than in lower latitudes) continues. (Redrawn by NOAA NCDC)

P. How are the oceans affected by climate change?

The oceans cover more than two-thirds of the Earth's surface and play a very important role in regulating the Earth's climate and in climate change. Today, the world's oceans absorb more than 90% of the energy captured by human-emitted carbon dioxide and other heat-trapping gases. This extra energy warms the ocean, causing it to expand. This in turn causes sea level to rise. Of the 2.5 inches of global sea level rise observed over the last 35 years, about 1 inch is due to this warming of the water. Most of the rest is due to the melting of glaciers and ice sheets. Ocean levels are projected to rise another 1 to 4 feet over this century, with the difference largely depending on the amount of global temperature rise and polar ice sheet melt.

Observations from past climate combined with climate model projections of the future suggest that over the next 100 years the Atlantic Ocean's overturning circulation, the "Ocean Conveyor Belt," could slow down as a result of climate change. These ocean currents carry warm water northward across the equator in the Atlantic Ocean, warming the north Atlantic (and Europe) and cooling the South Atlantic. A slowdown of the Conveyor Belt would increase regional sea level rise along the east coast of the United States and change patterns of temperature in Europe and rainfall in Africa and the Americas, but would not lead to global cooling.

Warming ocean waters also affect marine ecosystems like coral reefs, which can be very sensitive to temperature changes. When water temperatures become too high, coral expel the algae, called zooxanthellae, which help nourish them and give them their vibrant color. This is known as coral bleaching. If the high temperatures persist, the coral die.

In addition to the warming, the acidity of seawater is increasing. The oceans absorb about 25% of the carbon dioxide released by fossil fuel burning every year. The dissolved carbon dioxide reacts with seawater to form carbonic acid, which increases its acidity and reduces the availability of calcium carbonate corals need to maintain their structure. Both the increased acidity and higher temperature of the oceans are expected to negatively affect corals over the coming decades and beyond.

Coral Bleaching

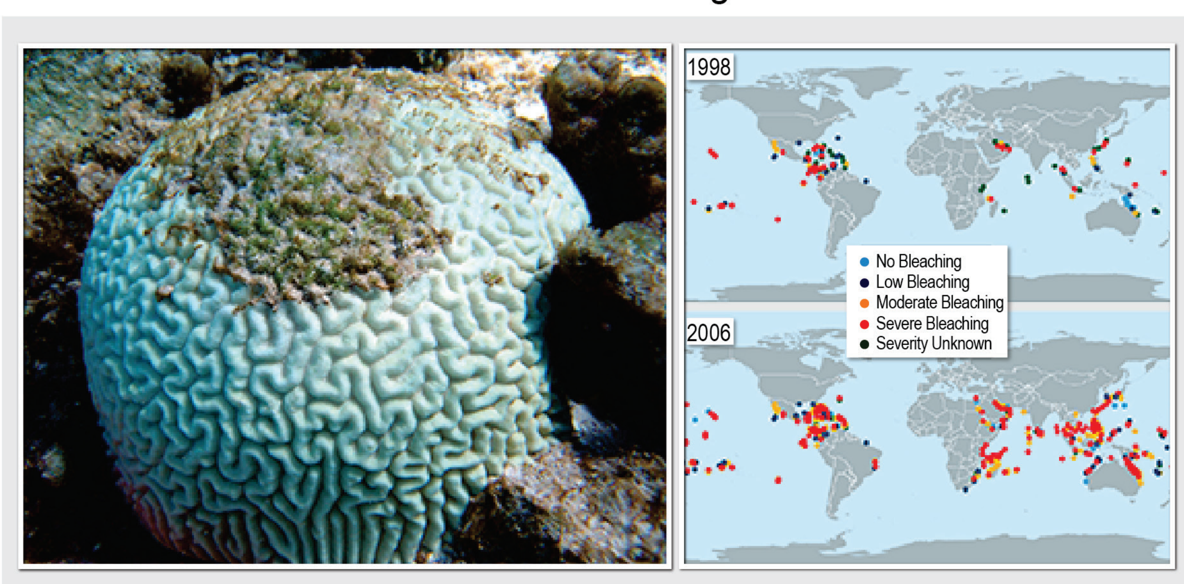

Figure 22: Coral Bleaching

Caption: (left) Bleached brain coral (Credit: NOAA); (right) The global extent and severity of mass coral bleaching have increased worldwide over the last decade. (Source)

Q. What is ocean acidification?

As human-related emissions of carbon dioxide build up in the atmosphere, excess carbon dioxide is also dissolving into the oceans, where it reacts with seawater to form carbonic acid. Calcium carbonate minerals are the building blocks for the skeletons and shells of many marine organisms. In areas with many marine organisms, the seawater is supersaturated with calcium carbonate minerals. This means there are abundant building blocks for calcifying organisms to build their skeletons and shells. However, continued ocean acidification is lowering the concentrations of these minerals in many parts of the ocean, affecting the ability of some organisms to produce and maintain their shells.

Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units, representing approximately a 30% increase in acidity. The oceans will continue to absorb carbon dioxide from human activities and become even more acidic in the future. Projections of carbon dioxide levels indicate that by the end of this century the surface waters of the ocean could be as much as 150% more acidic, resulting in a pH that the oceans haven't experienced for more than 20 million years.

Ocean acidification is expected to affect ocean species to varying degrees. Photosynthetic algae and seagrasses may benefit from higher CO_2 conditions in the ocean, as they require CO_2 to live just like plants on land. On the other hand, studies have shown that a more acidic environment has dramatic negative effects on some calcifying species, including oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. When shelled organisms are at risk, the entire food web may also be at risk.

Figure 23: Ocean Acidification and the Food Web

Caption: The Pteropod, or "sea butterfly," is a tiny sea creature about the size of a small pea. Pteropods are eaten by organisms ranging in size from tiny krill to whales and are a major source of food for North Pacific juvenile salmon. The photos above show what happens to a pteropod's shell when placed in seawater with a pH and carbonate levels projected for the year 2100. The shell slowly dissolves after 45 days. Photo credit: National Geographic Images.

R. Should we trust the computer models of the Earth's climate?

People depend on results generated by computer models every day. They are used to design airplanes, automobiles, houses, and control all of the electronics we use in our daily lives. In studying climate change, models serve as an important way to integrate different kinds of knowledge of how the climate system works.

Climate models are based on mathematical and physical equations representing the fundamental laws of nature and the many processes that affect the Earth's climate system. When the atmosphere, land, and ocean are divided up into small grid cells and these equations are applied to each grid cell, they can capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over the longer timeframes, these models simulate wind patterns, high and low pressure systems, and other weather characteristics that make up climate.

Climate models are used to analyze past changes in the long-term averages and variations in temperature, precipitation, and other climate indicators, and to make projections of how these trends may change in the future. Today's climate models do a good job at reproducing the broad features of the present climate and changes in climate, including the significant warming that has occurred over the last 50 years. Hence, climate models can be useful tools for testing the effects of changes in the factors that drive changes in climate, including heat-trapping gases, particulates from human and volcanic sources, and solar variability.

Climate models require enormous computing resources, especially to capture the geographical details of climate. Today's most powerful supercomputers are enabling climate scientists to more thoroughly examine effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase another 100 fold or more, permitting even more details of the climate to be explored.

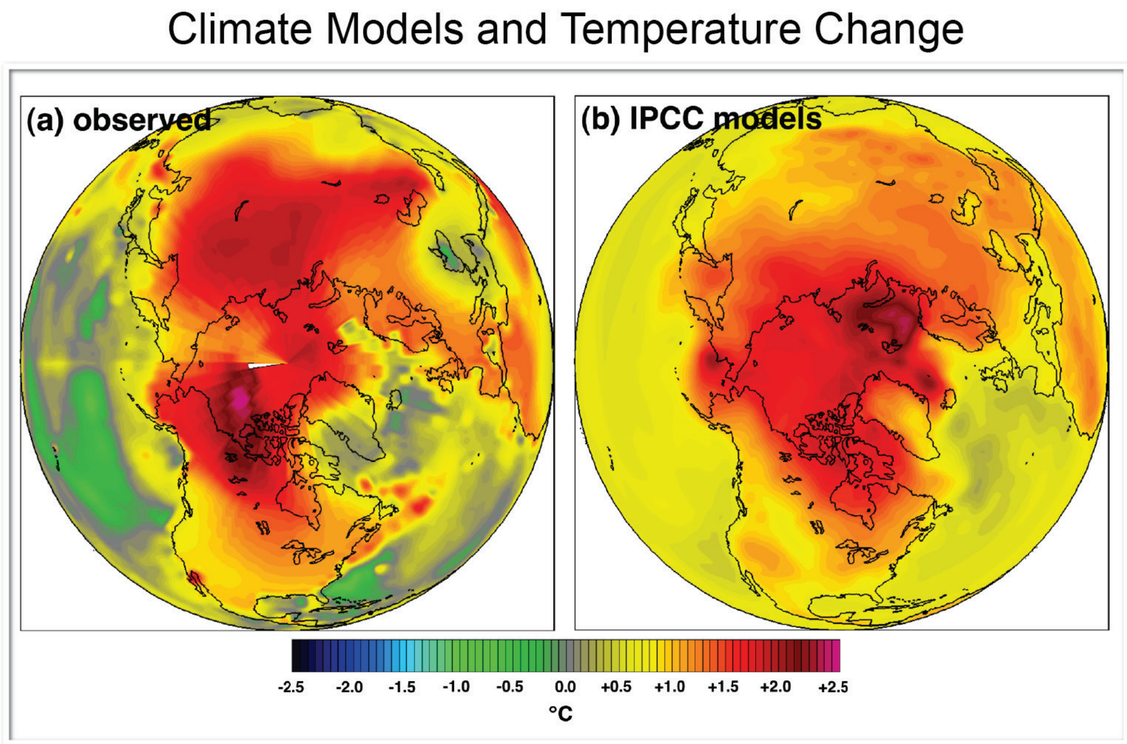

Figure 24: Climate Models and Temperature Change

Caption: The geographical pattern and approximate magnitude of temperature changes over 50 years (1957-2006) from observational data (left) is approximately captured by computer models of the climate system (right). The pattern from the computer models is an average based on 15 different global climate models used in the IPCC's Fourth Assessment Report.

S. What are the key uncertainties about climate change?

It is impossible to predict the future with absolute certainty. Nonetheless, available evidence gives scientists confidence that humans are having a significant effect on climate and will continue to do so over this century and beyond. In particular, continued use of fossil fuels and resulting emissions will significantly alter climate and lead to a much warmer world. The precise amount of future climate change that will occur over the rest of this century is uncertain due to several reasons.

First, estimates of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change as a result of population, energy, technology, and economics. Society may choose to reduce emissions, or to continue to increase them. The differences in projected future climate under different emission scenarios are generally small for the next few decades. By the second half of the century, however, human choices, as reflected in these scenarios, become the key source of uncertainty in future climate change. And human choices are nearly impossible to predict.

A second source of uncertainty is natural variability, which affects climate over timescales from months to decades. These natural variations are largely unpredictable and are superimposed on the warming from increasing heat-trapping gases. Uncertainty in the future output from the Sun is another source of variability that is independent of human actions. Estimates of past changes in solar variability over the last several millennia suggest that the magnitude of solar effects over this century are likely to be small compared to the magnitude of the climate change effects projected from human activities.

A third source of uncertainty is scientific limitations. The Earth's climate system is complex, and continues to challenge scientists' understanding of exactly how it may respond to human influences. Observations of the climate system have grown substantially since the beginning of the satellite era, but are still limited. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and turbulent mixing of air), although all of these representations are within the range of observations. As a result, different models produce slightly different projections of change, even when the models use the same scenarios.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in future projections. In some cases, these feedbacks are already documented as occurring: for example, as the Arctic warms, methane and carbon dioxide trapped in permafrost is being released into the atmosphere, increasing the initial warming due to human emissions of heat-trapping gases (see CAQ T). However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, determined not only from the differences in the "climate sensitivity" among models but also from information about climate changes in the past.

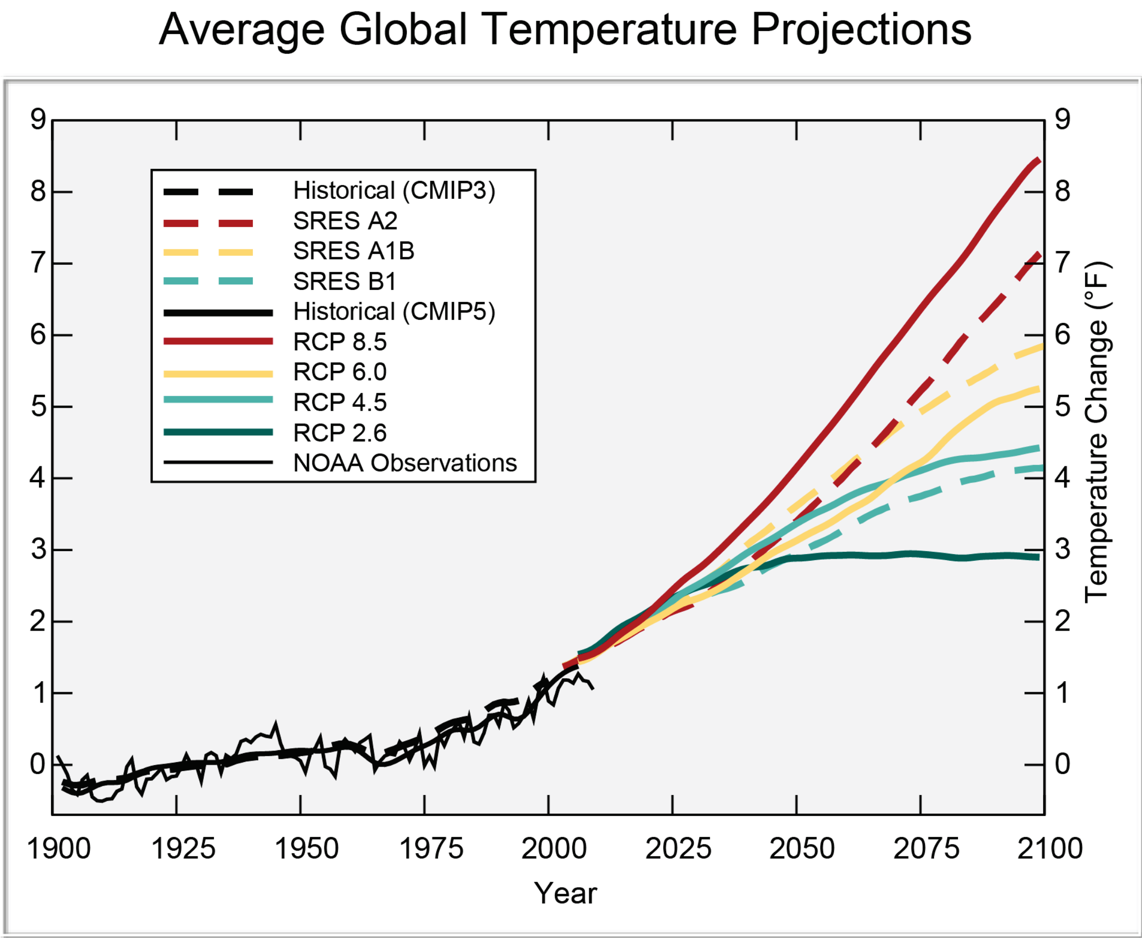

Figure 25: Average Global Temperature Projections

Caption: Projected global average annual temperature changes (degrees Fahrenheit) for multiple future emissions scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models. The solid lines are results from the most recent generation of climate models. Differences in these projections are principally a result of differences in the emissions scenarios. (Figure source: Michael Wehner, LBNL. Data from CMIP3, CMIP5, and NOAA.)

T. Are there tipping points in the climate system we should be concerned about?

Most climate studies have considered only relatively gradual, continuous changes in the Earth's climate system. However, there are a number of potential tipping points in the climate system, at which a small change in, for example, heat-trapping gas emissions, can cause a substantial change in the future state of a part of the climate system.

Scientists have identified several elements in the climate system that could pass a tipping point this century and/or change substantially over this millennium under projected climate change. The tipping points have been identified based on observations of past abrupt climate changes, recent observations showing abrupt changes underway (for example, in the Arctic), process-based understanding of the dynamics of the climate system, and climate simulations showing tipping points in future projections.

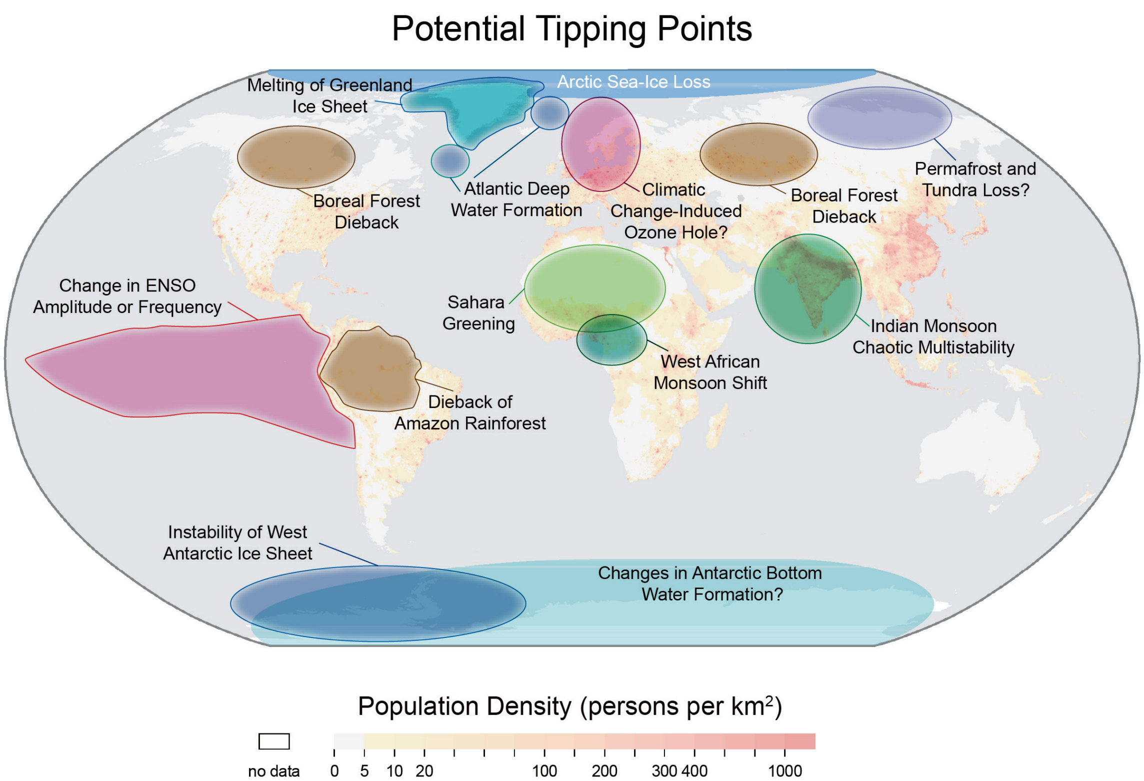

Figure 26: Potential Tipping Points

Caption: Map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain. (From Lenton et al. 2008).

We should be most concerned about those tipping points that are the most imminent (and thus the least avoidable), and those that would have the largest negative impacts. Generally, the more rapid and less reversible a transition is, the greater its impacts. Additionally, any amplifying effect on global climate change increases concern. For example, thawing permafrost releases heat-trapping gases, which leads to further warming and an acceleration of permafrost thaw. In general, a tipping point may exist if a change of one element triggers additional processes that amplify the original change.

The proximity, rate, and reversibility of tipping points has been assessed through a mixture of climate modeling, literature review, and expert elicitation, but there is a need for more research into their impacts.

Climate scientists cannot predict when tipping points will be crossed, because of uncertainties in the climate system and because we do not know what pathway future emissions will take. But that does not mean that the risk should not be taken seriously. To use a medical analogy, just because your doctor cannot tell you the precise date and time that you will have a heart attack does not mean you should ignore medical advice to reduce your risk. Medical science is imperfect, just like climate science, but it can provide very useful advice regarding the risk of our actions and choices.

Risk Matrix for Climate Tipping Points

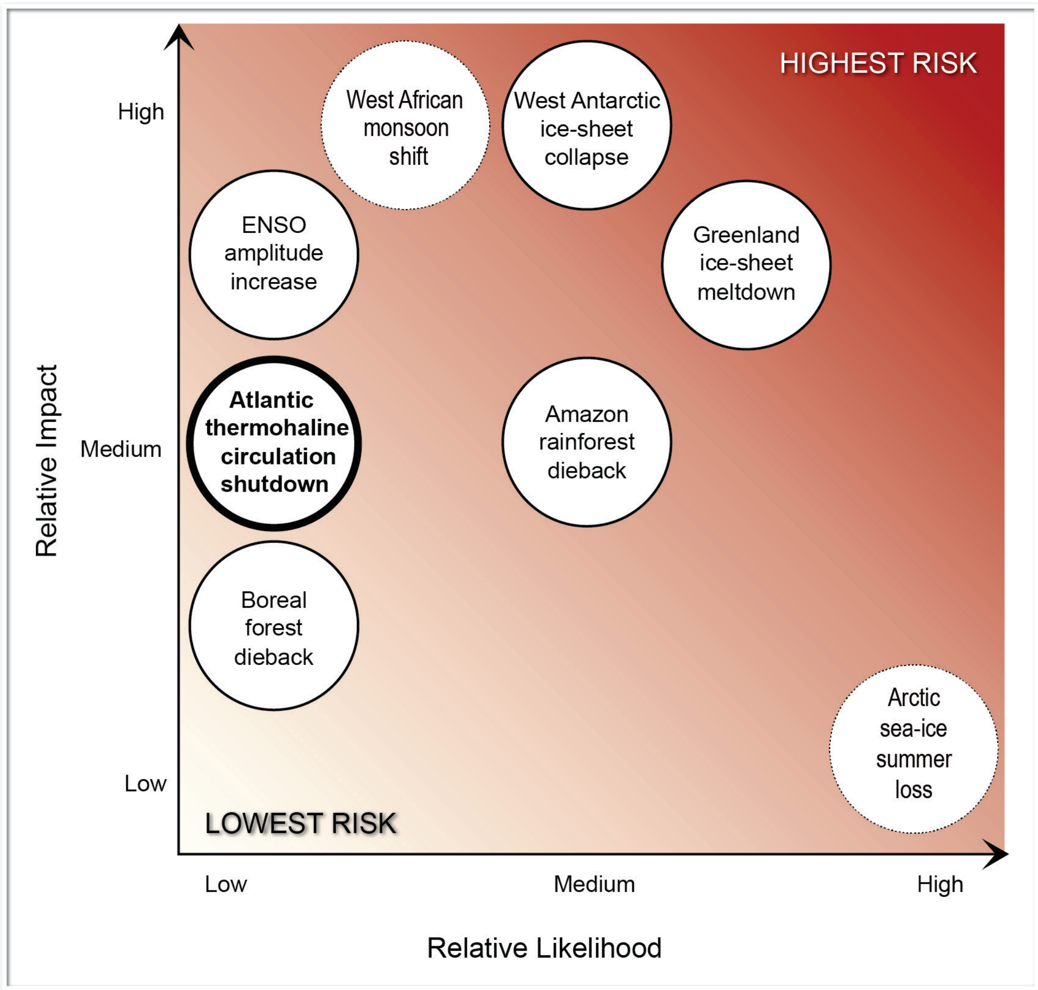

Figure 27: Risk Matrix for Climate Tipping Points

Caption: An example risk matrix for climate tipping points. Relative likelihoods and impacts are assessed on a five-point scale: low, low-medium, medium, medium-high and high. Likelihood information comes from review of scientific literature and expert elicitation (lighter rings indicate systems not considered in expert elicitation). Impacts are based on limited research and subjective judgment, and are relative to the one system (bold ring) with multiple impacts studies. Impacts are considered on a time horizon of 1,000 years, assuming minimal discounting of impacts on future generations. Note that most tipping point impacts would be high if placed on an absolute scale, compared with other climate eventualities. Figure source: redrawn from Lenton (2011)

U. Why should I care? How is climate change going to affect us?

Multiple lines of evidence show that climate change is happening as a result of human activities. Climate change is altering the world around us, and these changes will become more and more evident with each passing decade.

Climate change is already leading to more intense rainfall events and more extreme weather patterns. The changes in worldwide weather patterns will lead to more droughts in some area and more floods in others, as well as more frequent heat waves over many land areas. The risk associated with wildfires in the western U.S. is increasing, and coastal inundation is becoming a common occurrence in low-lying areas. Water supply availability is changing in many parts of the U.S.

Everyone on Earth will be affected by the changes that are occurring. To limit risks and maximize opportunities associated with the changes, people everywhere need to understand how climate change is going to affect them and what they can do to cope. There is significant likelihood that climate change will affect ecosystems and human systems – such as agricultural, transportation, water resources, and health infrastructure – in ways we are only beginning to understand. Moreover, climate change can interact with other stressors, such as population increase, land use change, and economic and political changes, in ways that we may not be able to anticipate, compounding the risks.

Although some impacts will likely be beneficial within limited sectors and regions, overall these changes will be costly. We do not have a choice about whether we will adapt, the choice is between proactive adaptation (where we plan ahead to limit the impacts) or reactive adaptation (where responses occur after the damage is already unavoidable).

In general, the larger and faster the changes in climate are, the more difficult it will be for human and natural systems to adapt. The climate system has been relatively stable during the time that human civilizations have been built, but the current pace of change is accelerating. Essentially, today's built infrastructure has been developed based on an assumption of "stationarity" in the climate. This assumption is likely no longer valid. This presents both challenges and opportunities for society as a whole as well as individual sectors and regions.

Potential Effects of Climate Change

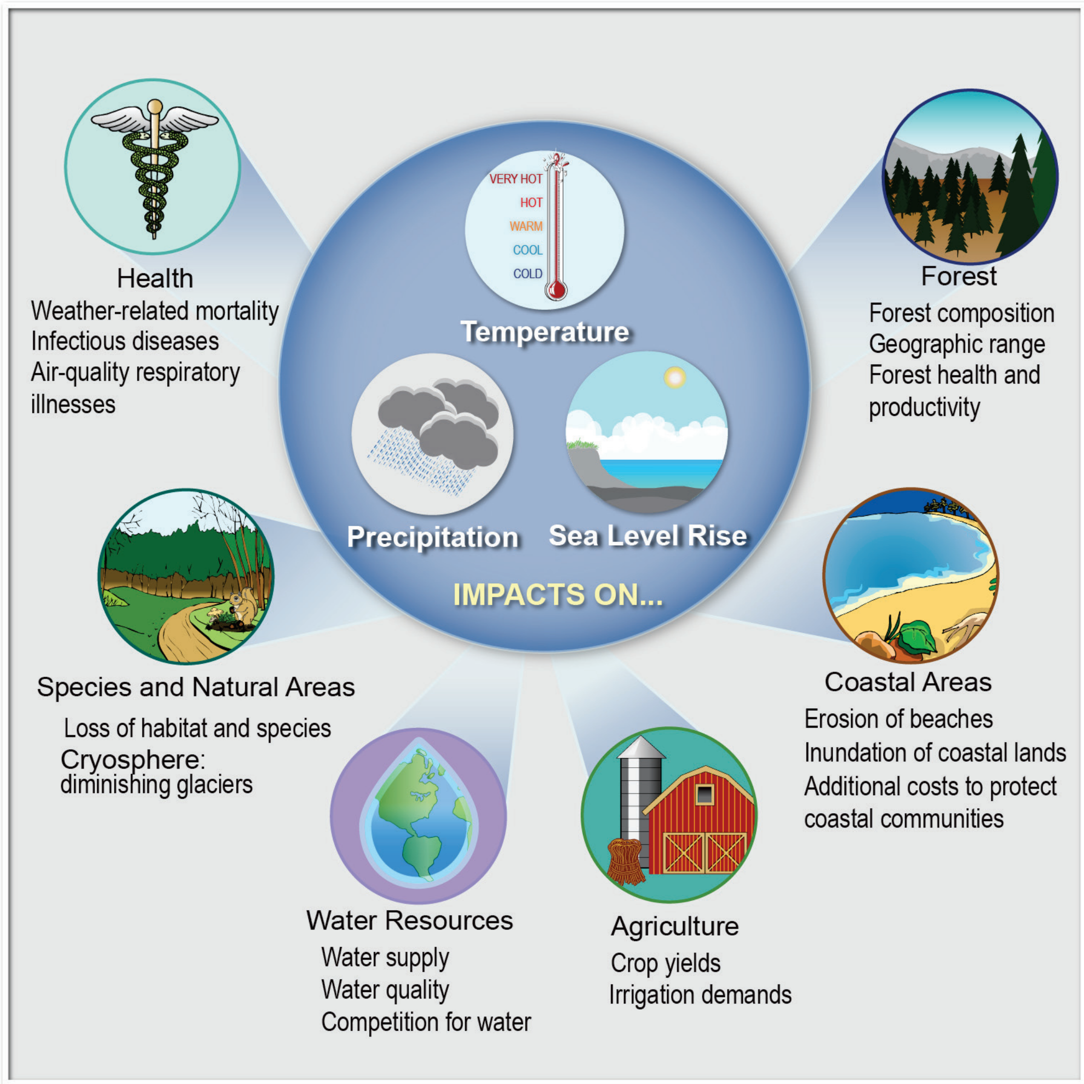

Figure 28: Potential Effects of Climate Change

Caption: Climate change is likely to affect us in many ways. (Figure source: adapted from Phillipe Rekacewicz UNEP/GRID-Arendal 2012; Figure is from "Vital Climate Graphics" collection)

V. Won't more warming be good for us?

There are currently many parts of the globe (in the higher latitudes) that are colder than most people find comfortable, and it is easy to imagine how increasing temperatures in these regions could have positive effects. A longer period of frost-free days resulting in a longer growing season by itself can have positive effects on agricultural productivity. But it's not that simple – concerns about weeds, insects, and diseases in crops also increase with higher temperatures. Reduction in sea ice in the Arctic will open more shipping possibilities, but the higher temperatures in this region also open the potential for many negative consequences, including: major disruptions of ecosystems that are important sources of food and other valued products; habitat loss for endangered species; loss of culturally valued practices and subsistence lifestyles; loss of permafrost that may currently support roads, houses, and other infrastructure; and increases in wildfire.

Changes in average temperatures may have beneficial effects depending on where you live and on the nature of local economic activity. However, it is unlikely that rapid changes in extreme temperatures (which become more likely as heat-trapping gas concentrations rise) will result in positive outcomes for people or ecosystems because, on the whole, it is more difficult to be well-prepared for sudden changes.

Also, climate change is much more than changes in temperature. Changes are also occurring in the amount, intensity, frequency, and type of precipitation. For example, there has been an increase in the number of very heavy precipitation events across the U.S. over the last half century. Analyses of the frequencies of large-precipitation storms show that such events are occurring more often than in the past.

Precipitation is generally increasing at higher northern latitudes and decreasing in the tropics and subtropics over land. In general, wet areas are getting wetter and dry areas are getting drier. Scientific analyses also indicate a strong link between changing trends in severe weather events and the changing climate. Analyses also suggest that these severe heat and extreme precipitation events will become more common in the future.

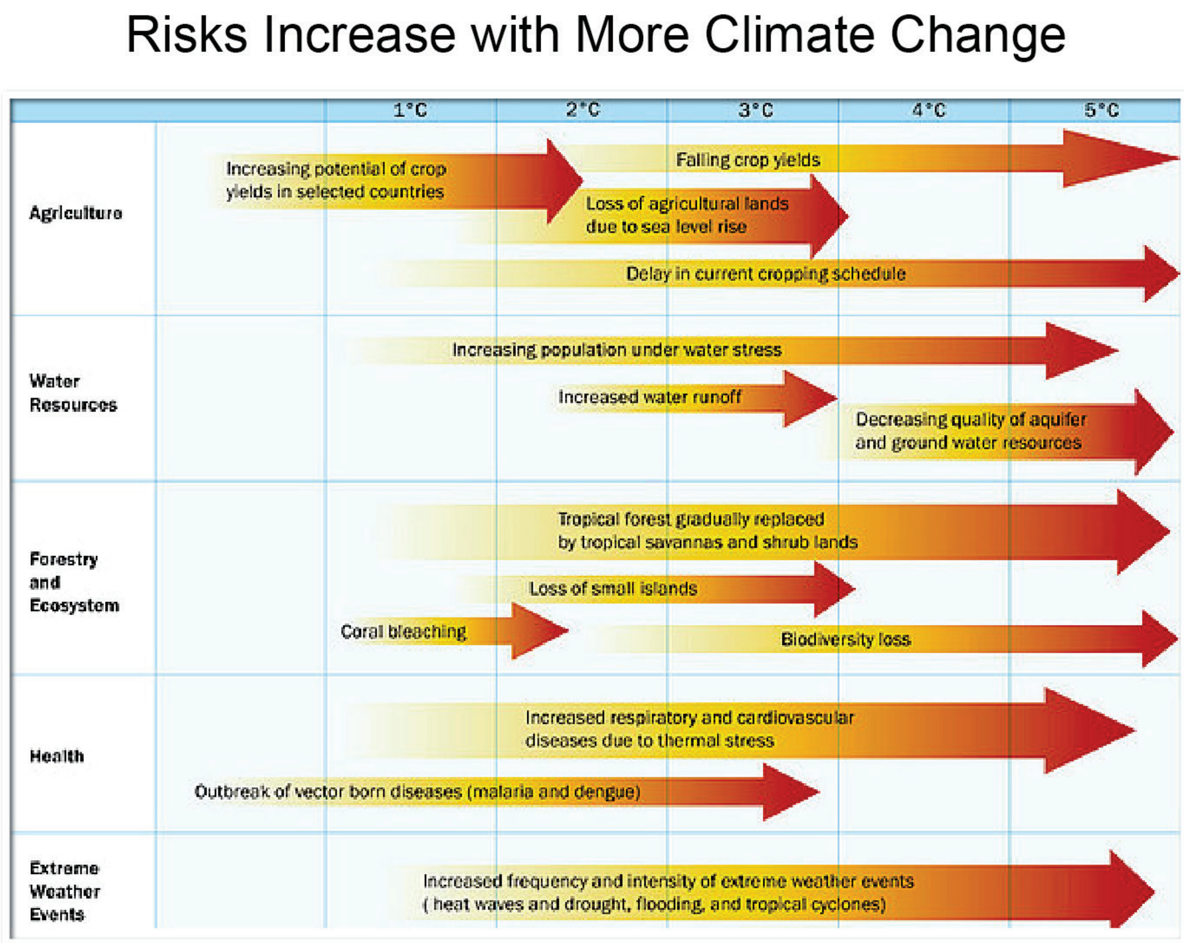

Figure 29: Risks Increase with More Climate Change

Caption: The risks from impacts increase with the amount of climate change. (Adapted from Stern 2006)

W. Who will be most affected by climate change?

All of us will be affected by climate change. This is not surprising when we consider that people and other life on Earth have adapted over time to the climate we have had in localities for many hundreds of years. Today, changes in climate are occurring so rapidly that it may be difficult to adapt to the changes. This is especially true for vulnerable groups within society such as the poor, the very young, and some older people who have few resources to adapt to changes in climate, which may bring higher food prices, increased water scarcity, environmental degradation, and coastal flooding. Also, two-thirds of the world's largest cities lie within a few feet of sea level, raising major concerns about the potential for climate change to create millions of new environmental refugees.

Longer, more intense, and more frequent heat waves increase concerns about heat-related death and illness. Without further major decreases in pollution emissions, it is virtually certain that air quality in cities will decline, since greater heat also worsens air pollution such as ozone or smog. Insect-borne illnesses are also likely to increase in some areas as many insect ranges expand. The health effects of climate change are especially serious for the very young, very old, or for those with heart and respiratory problems. However, higher winter temperatures may reduce the negative health impacts from cold weather as well.

Ecosystems are also affected by climate change, in particular, fragile ecosystems have difficulty adapting to even small changes. As the climate continues to warm, major changes are expected in ecosystem structure and function, interactions among species, and species' geographic ranges, with predominantly negative consequences for biodiversity. Higher temperatures and precipitation changes will affect the habitats and migratory patterns of many types of wildlife. The ranges and distributions of many species will change; some species that cannot move or adapt may face extinction. In addition, climate changes such as increased floods and droughts are predicted to increase the risk of extinction for some plant and animal species, many of which are already at-risk due to other non-climate related factors.

Climate Variability by Nation

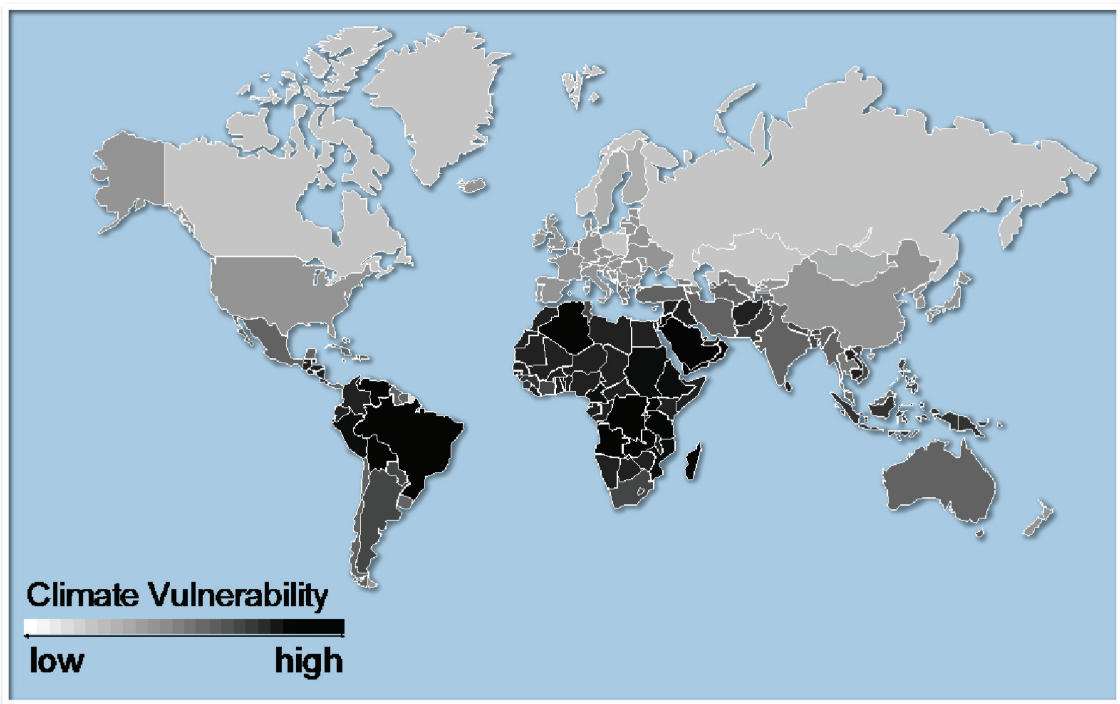

Figure 30: Climate Variability by Nation

Caption: Projected climate vulnerability interpolated to individual nations. (Source: Samson et al. 2011)

X. What can be done? Are there solutions?

There are multiple paths forward in response to climate change. One choice is do nothing and try to deal with the consequences. However, a number of economic analyses have concluded that the costs from inaction would be much larger than the costs of action. Technological "fixes," such as "geoengineering," may be possible but look to be extremely risky (see CAQ Z). Another choice is to significantly reduce the emissions of heat-trapping gases by changing the way that we use energy.

Increased efficiency in energy use is important, as is the increased use of energy technologies that do not produce carbon dioxide. For example, because about 28% of the energy used in the U.S. is used for transportation, changing the types of fuel that we use to those that do not contribute significantly to heat-trapping gas emissions (such as biofuels) and driving more efficient vehicles is one obvious path forward. A large amount of energy in the U.S. is also used to heat and cool buildings, so changes in building design could dramatically reduce energy use. There are many pathways that can help prevent the largest of the potential impacts on humanity and ecosystems from climate change.

Adaptation will also be necessary. Because impacts are already occurring and anticipated to increase at least in the short term, adaptation to the impacts of climate change will be required. Adaptation decisions range from being better prepared for extreme events such as floods and droughts, to identifying economic opportunities that come from investments in adaptation and mitigation strategies and technologies, to integrating considerations of new climate-related risks into city planning, public health and emergency preparedness, and ecosystem management.

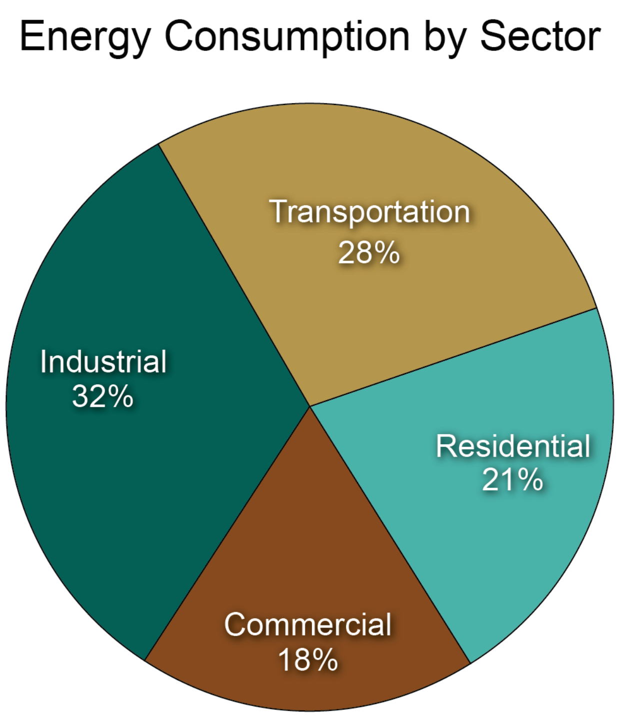

Figure 31: Energy Consumption by Sector

Caption: Percentage of energy consumed by various economic sectors in the United States in 2006. Percentages do not sum to 100% because of individual rounding. (Source: NRC 2008).

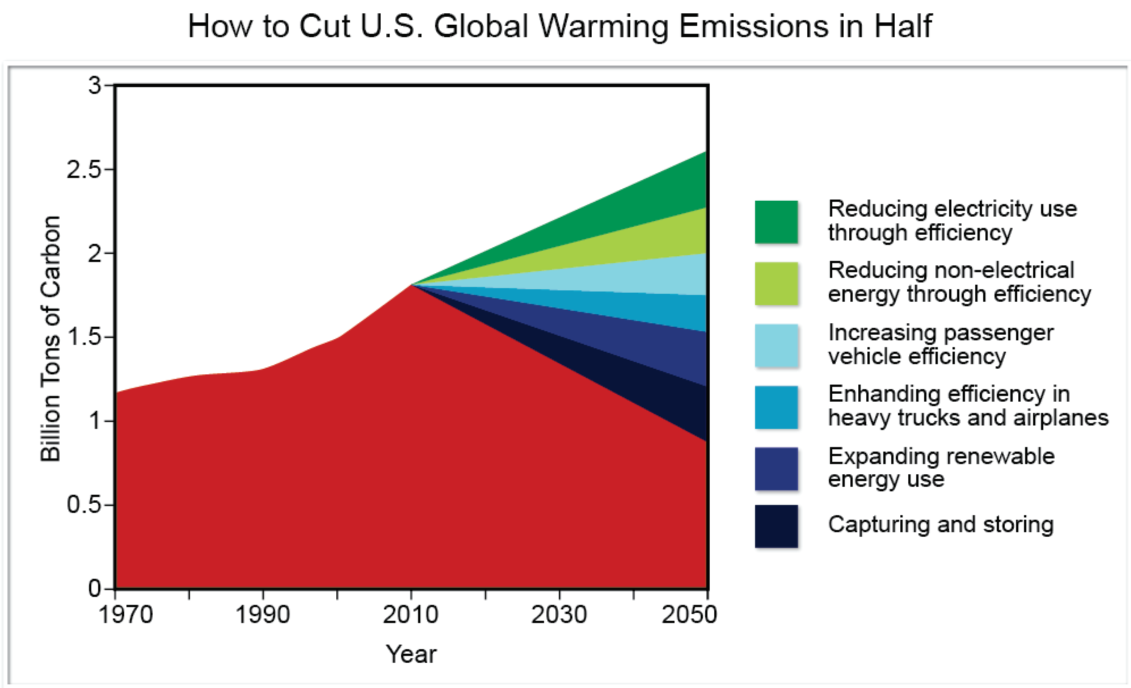

Figure 32: How to Cut U.S. Global Warming Emissions in Half

Caption: Many pathways to reduce energy use, improve efficiency, and adopt new technologies could contribute to a reduction in U.S. emissions. (Source: Pacala and Socolow, 2004 and Kuuskraa et al., 2004)

Y. Is it better to act now or later?

The effects on climate from current emissions of carbon dioxide and other heat-trapping gases can take decades to fully manifest. The resulting change in climate and the impacts of those changes can then persist for a long time. Waiting longer to manage emissions will result in more impacts, potentially exceeding the ability of human or natural systems to adapt. Thus it is not surprising that recent reports from the U.S. National Academy of Sciences, including America's Climate Choices (NRC 2011) and America's Energy Futures (NAS 2010), have concluded that the environmental, economic, and humanitarian risks posed by climate change indicate a pressing need for substantial action to limit the magnitude of climate change and to prepare to adapt to its impacts. They also concluded that substantial reductions of heat-trapping gas emissions should be among the nation's highest priorities.

The National Academy of Sciences and others have concluded that acting now will reduce the risks posed by climate change and the pressure to make larger, more rapid, and potentially more expensive reductions later. Most actions taken to reduce vulnerability to climate change impacts are investments that make sense economically because they also offer protection against natural climate variations and extreme events as well. In addition, crucial investment decisions made now about equipment and infrastructure can "lock in" heat-trapping gas emissions for decades to come. Finally, while it may be possible to scale back or reverse many responses to climate change, it is difficult or impossible to "undo" climate change, once manifested.

Current efforts at local and state levels, and by the private sector, are important, but are insufficient to limit warming to the lower emissions scenarios described throughout this report. Thus, numerous analyses have called for policies that establish coherent national goals and incentives, and that promote strong U.S. engagement in international-level response efforts. The National Academy of Sciences found that the inherent complexities and uncertainties of climate change will be best met by applying an iterative risk management framework and by making efforts to significantly reduce heat-trapping gas emissions; prepare for adapting to impacts; invest in scientific research, technology development, and information systems; and facilitate engagement between scientific and technical experts and the many types of stakeholders making America's climate choices.

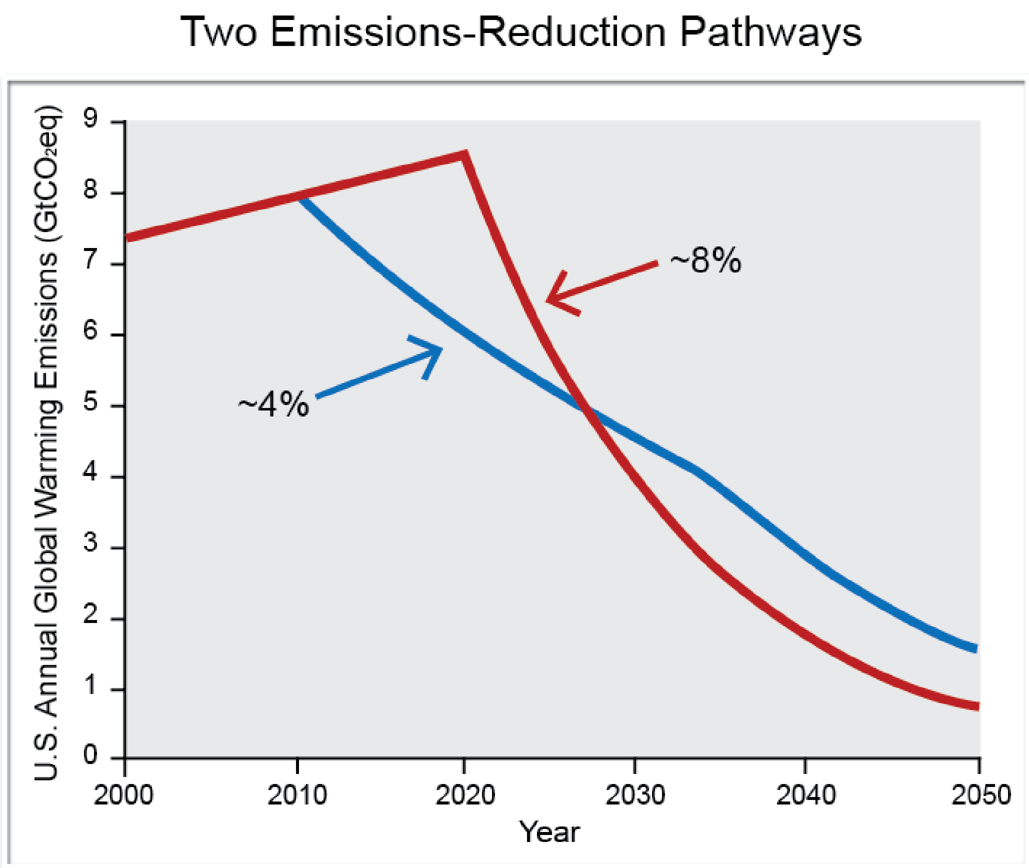

Figure 33: Two Emissions-Reduction Pathways

Caption: This graph shows why earlier action to reduce emissions would be less difficult and expensive than delayed action. The lines show two pathways to achieve reductions of 80% below 2000 emissions by 2050, a level agreed by international negotiations to be a limit above which impacts become more severe. Starting in 2010 (blue line) requires a 4% per year reduction, while waiting until 2020 (red line) doubles the rate at which emissions must be reduced to 8%. (Source: UCS 2007)

Z. Can we reverse global warming?

Even if all human-related emissions of carbon dioxide and the other heat-trapping gases were to stop today, the Earth's temperature would continue to rise for a number of decades and then slowly begin to decline. However, because of the complex processes controlling carbon dioxide concentrations in the atmosphere, even after more than a thousand years, the global temperature would still be higher than it was in the preindustrial period. As a result, without technological intervention, it will not be possible to totally reverse climate change. We do face a choice between a little more warming and lot more, however. The amount of future warming will depend on our emissions pathway.

In theory, it may be possible to reverse global warming through technological interventions called geoengineering. There are two types of geoengineering approaches that have been proposed to alter the climate system: 1) removal of atmospheric carbon dioxide, and 2) altering the amount of the Sun's energy that reaches the Earth (referred to as "solar radiation management").

Various techniques for removal of atmospheric carbon dioxide, the longest-lived of the heat-trapping gases, have been proposed. At this time, however, there is no indication that any of them could be implemented on a large enough scale to have a significant effect. Investments in limiting emissions, combined with capturing and storing carbon, could possibly reverse the warming trend, but it remains to be seen if this is feasible.

Artificial injection of stratospheric particles and cloud brightening are two examples of "solar radiation management" techniques. The known cooling effect that some types of particles have on the atmosphere has led to the proposal of an array of possible geoengineering projects, especially with the goal of offsetting the warming until more non-fossil fuel energy is put into place. However, the climate system is complex and experimenting without complete understanding could result in unintended and potentially dangerous side effects on our health, ecosystems, agricultural yields, and even the climate itself. Even if such engineering approaches were economically feasible, the potential impacts on the environment need to be better understood. One important consideration regarding solar radiation management is that ocean acidification would still continue even if warming could otherwise be reduced. Much more research is needed to see if such approaches could be environmentally feasible. In the meantime, there are significant concerns about ecological and other side effects of some of these technologies.

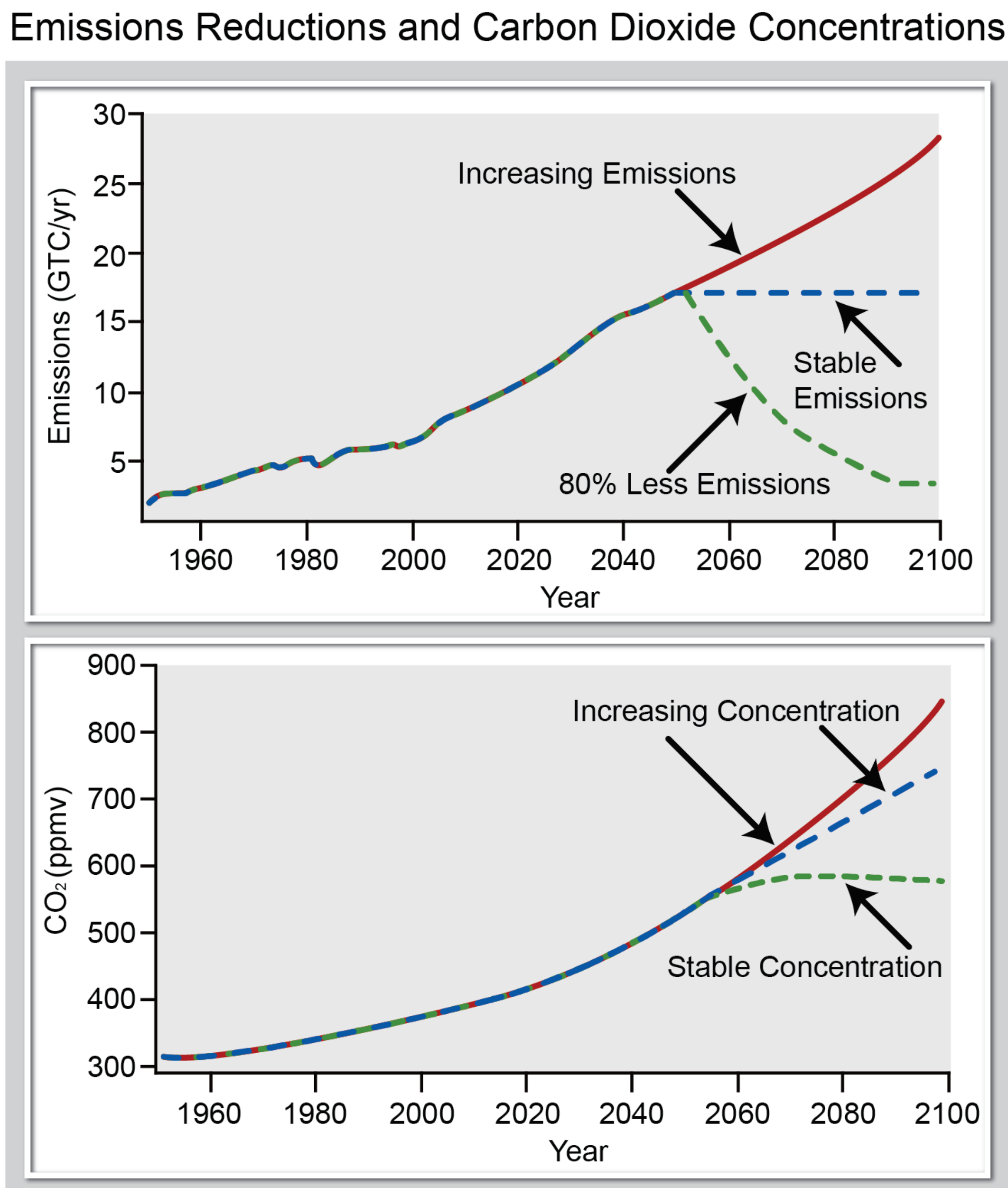

Figure 34: Emissions Reductions and Carbon Dioxide Concentrations

Caption: Because emissions of carbon dioxide are greater than the sinks that remove it, emissions reductions larger than about 80% (green line-top graph) are required if concentrations are to be stabilized (green line-bottom graph). The lower graph shows how carbon dioxide concentrations would be expected to evolve depending upon emissions for one illustrative case, but this applies for any chosen target. From (NRC 2011)

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Appendix: The Science of Climate Change

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Key Messages

1. **Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.**

2. **Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.**

3. **Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.**

4. **Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The “fingerprints” of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.**

5. **Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.**

6. **Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging many models, many clear trends emerge.**

7. **Scientific understanding of observed temperature changes in the U.S. has greatly improved, confirming that the U.S. is warming as expected in response to global climate change. This warming is expected to continue.**

8. **Many other indicators of rising temperatures have been observed in the U.S. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.**

9. **There have been observed trends in some types of extreme weather events, and these are consistent with rising temperatures. These include increases in: heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate changes' effects on other types of extreme events continues.**

10. **Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire U.S.**

11. **Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land and sea-based ice is expected to continue with further warming.**

12. **Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of temperature change and on the ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.**

Appendix: The Science of Climate Change

This Appendix provides further information and discussion on climate science beyond that presented in the chapter *Our Changing Climate.* The focus here is also on the observations, model simulations, and other analyses that explain what is happening to climate at the national and global scales, why these changes are occurring, and how climate is projected to change throughout this century.

As noted in the main chapter, changes in climate, and the nature and causes of these changes, have been comprehensively discussed in a number of other reports (Karl et al. 2009), including the global climate assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Academy of Sciences. This Appendix is consistent with the main chapter in providing a focus on the ongoing changes of climate in the United States. These changes are placed into a global context in the first few key messages, followed by an elaboration on the changes having the greatest impacts (and potential impacts) on the United States. Throughout the Appendix, there is more information on attribution, spatial and temporal detail, and physical mechanisms than could be covered within the length constraints of the main chapter.

The projections described in this Appendix are based, to the extent possible, on the CMIP5 model simulations. However, given the timing of this report relative to the evolution of the CMIP5 archive, some projections are necessarily based on CMIP3 simulations. We have attempted to identify the CMIP version in those instances when the source of the projections is unclear. (See Key Message 5 for more on these simulations and related emissions scenarios).

Key Message 1.

Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.

The Earth's climate is constantly changing over time. Without external forcing, changes are the result of complex interactions between the climate system's atmosphere, ocean, land surface, and living things. This natural variability is internal to (occurs within) the climate system. Internal variability of temperature on decadal time scales is quite small (less than 0.5°F)(Swanson et al. 2009) compared to the changes that can occur due to external forcers. External drivers that directly affect climate include natural phenomena, such as variations in the energy received from the Sun, as well as human-driven increases in carbon dioxide (CO_2) and other heat-trapping gases. Feedback mechanisms triggered by changes in the climate system are external drivers that indirectly affect climate by increasing or dampening an initial change.

The natural greenhouse effect is key to understanding how human activities can affect the Earth's climate. The greenhouse effect is a natural process, first discovered in 1824 and validated by observations in 1859. Heat-trapping gases, including water vapor, carbon dioxide, ozone, methane, and nitrous oxide, absorb some of the heat given off by the Earth's surface and lower atmosphere. They then radiate much of the energy back toward the surface, effectively trapping the heat inside the climate system. Without this natural greenhouse effect, the average surface temperature of the Earth would be about 60°F colder than it is today.

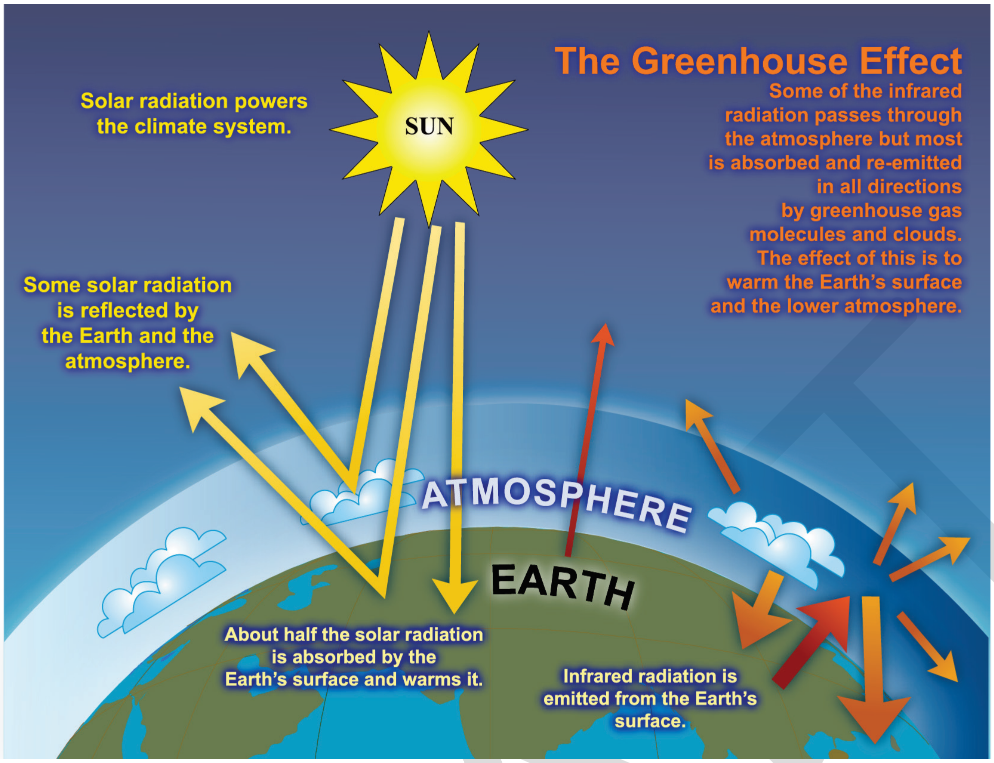

Figure 1: The Greenhouse Effect

Caption: Diagram illustrating the greenhouse effect. (Figure Source: IPCC 2007)

Water vapor is the single most important gas responsible for the natural greenhouse effect. However, the amount of water vapor in the atmosphere depends on temperature. This means that water vapor is a feedback, not a direct forcing on climate. Observational evidence shows that, in terms of direct forcing, carbon dioxide is the most important heat-trapping gas in the Earth's atmosphere (Lacis et al. 2010). This is because carbon dioxide and other gases, such as methane and nitrous oxide, do not condense and fall out of the atmosphere, whereas water vapor does (for example, as rain or snow). Together, heat-trapping gases account for between 26% and 33% of the total greenhouse effect (Schmidt et al. 2010). This is a range, rather than a single number, because some of the effects of water vapor overlap with those of other gases.

The concentrations of atmospheric CO_2 and other heat-trapping gases drive changes in the Earth's temperature, which in turn affects the levels of atmospheric water vapor and clouds that account for the remaining 66% to 80% of the greenhouse effect (Schmidt et al. 2010). Without the heat-trapping effects of carbon dioxide and the other greenhouse gases, climate simulations indicate that the greenhouse effect would not function, turning the Earth into a frozen ball of ice (Lacis et al. 2010).

Human activities are affecting the temperature of the Earth by altering the natural greenhouse effect. Burning fossil fuels (coal, oil, and natural gas), clearing of forests, and other human activities produce heat-trapping gases that build up in the atmosphere. This artificially intensifies the natural greenhouse effect, causing the planet to warm.

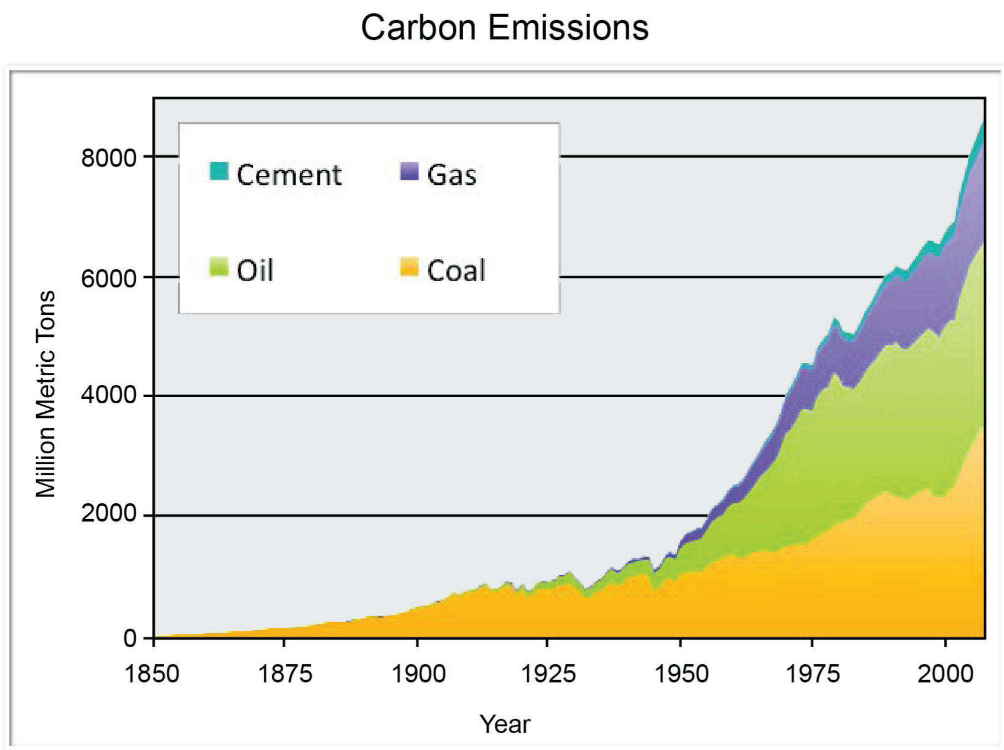

Figure 2: Carbon Emissions

Caption: Carbon emissions (in million metric tons) from burning coal, oil, and gas and producing cement, in units of million metric tons of carbon. (Source: Boden et al. 2010).

Carbon dioxide has been building up in the Earth's atmosphere since the beginning of the industrial era in the mid-1700s. Emissions and atmospheric levels of other important greenhouse gases, including methane, nitrous oxide, and halocarbons, have also increased because of human activities. While the levels of these gases in the atmosphere are relatively small compared to oxygen or nitrogen, their ability to trap heat is extremely strong. The human-induced increase in atmospheric levels of carbon dioxide and other heat-trapping gases is the main reason the planet has warmed over the past 50 years and has been a contributor to climate change over the past 150 years or more.

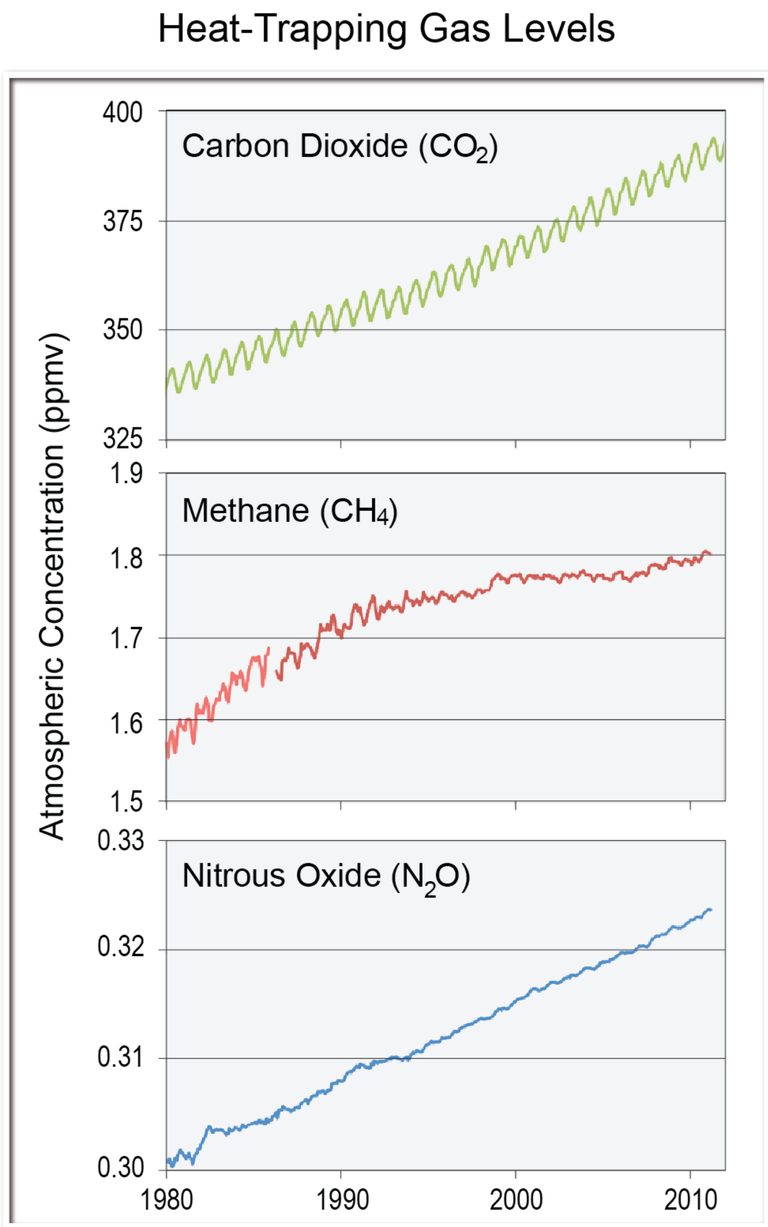

Figure 3: Heat-Trapping Gas Levels

Caption: Present-day atmospheric levels of carbon dioxide, methane, and nitrous oxide are notably higher than their pre-industrial averages of 280, 0.7, and 0.27 parts per million (by volume, or ppmv), respectively. Air sampling data from 1980 to the present show long-term increases due to human activities as well as short-term variations due to natural biogeochemical processes and seasonal vegetation growth. (Source: Khalil et al. 1993).

Carbon dioxide levels in the atmosphere are currently increasing at a rate of 0.5% per year. Atmospheric levels reached 392 parts per million in 2012, higher than anything the Earth has experienced in over a million years (the figure shows the ice core record for CO_2 levels over the last 800,000 years). Globally, over the past several decades, about 80% of carbon dioxide emissions from human activities came from burning fossil fuels, while about 20% came from deforestation and other agricultural practices. Some of the carbon dioxide emitted to the atmosphere is absorbed by the oceans, and some is absorbed by vegetation. About 45% of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation. The remainder has stayed in the atmosphere, where carbon dioxide levels have increased by 40% relative to pre-industrial levels.

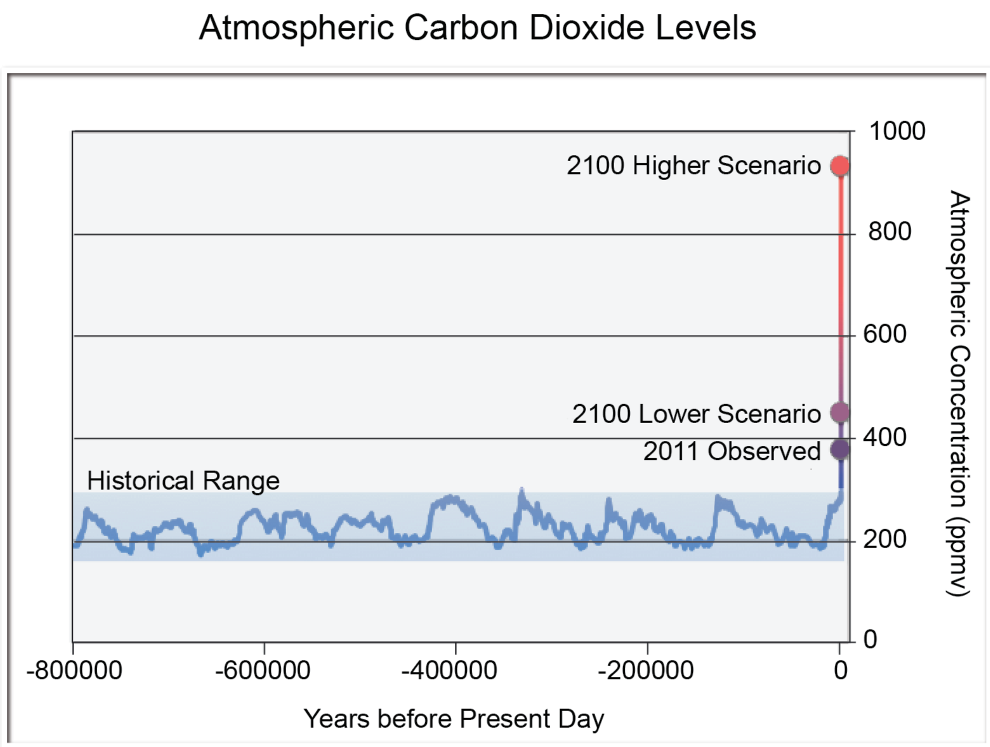

Figure 4: Atmospheric Carbon Dioxide Levels

Caption: Air bubbles trapped in an Antarctic ice core extending back 800,000 years document the atmosphere's changing carbon dioxide concentration. Over long periods, natural factors cause atmospheric CO_2 levels to vary between about 170 to 300 parts per million (ppm). As a result of human activities since the Industrial Revolution, CO_2 levels have increased to 392 ppm, higher than any time in at least the last 800,000 years. By 2100, additional emissions from human activities are projected to increase CO_2 levels to 420 ppm under lower emissions (the RCP 2.6 scenario, which would require substantial emissions reductions) and 935 ppm under higher emissions (the RCP 8.5 scenario, which assumes continued increases in emissions). Historical composite CO_2 record based on measurements from EPICA Dome C (Sources: 664-800kyr, (Lüthi et al. 2008); 393-664 kyr, (Siegenthaler et al. 2005); 0-22 kyr, (Monnin et al. 2001) and Vostok (22-393 kyr, (Pépin 2001; Petit et al. 1999; Raynaud 2005); future projections from RCP 2.6 and 8.5 (Source: Meinshausen et al. 2011).

Methane levels in the atmosphere have increased mainly as a result of agriculture including raising livestock (which produce methane in their digestive tracts); mining coal, extraction and transport of natural gas, and other fossil fuel-related activities; and waste disposal including sewage and decomposing garbage in landfills. About 70% of the emissions of atmospheric methane now come from human activities. Atmospheric amounts of methane leveled off from 1999-2006 due to temporary decreases in both human and natural sources, but have been increasing again since then. Since preindustrial times, methane levels have increased by 250% to their current levels of 1.85 ppm.

Other greenhouse gases produced by human activities include ***nitrous oxide, halocarbons, and ozone.*** Nitrous oxide levels are increasing primarily as a result of fertilizer use and fossil fuel burning. They have increased by about 20% relative to pre-industrial times.

Halocarbons are mostly man-made chemicals that have been manufactured to serve a specific purpose, from aerosol spray cans to refrigerant coolant. One type of halocarbon, long-lived chlorofluorocarbons (CFCs), was used extensively in refrigeration, air conditioning, and for various manufacturing purposes. However, in addition to being powerful heat-trapping gases, they are also responsible for depleting stratospheric ozone. Atmospheric levels of CFCs are now decreasing due to international agreements designed to protect the ozone layer. As emissions and atmospheric levels of halocarbons continue to decrease, their effect on climate will also shrink. However, some of the replacement compounds are potent heat-trapping gases, and their concentrations are increasing.

Over 90% of the ozone in the atmosphere is in the stratosphere, where it protects the Earth from harmful levels of ultraviolet radiation from the Sun. In the lower atmosphere, however, ozone is an air pollutant and also an important heat-trapping gas. Upper-atmosphere ozone levels have decreased because of human emissions of CFCs and other halocarbons. However, lower-atmosphere ozone levels have increased because of human activities, including transportation and manufacturing. These produce what are known as ozone precursors: air pollutants that react with sunlight and other chemicals to produce ozone. Since the late 1800s, average levels of ozone in the lower atmosphere have increased by more than 30% (Lamarque et al. 2005). Much higher increases have been observed in areas with high levels of air pollution, and lesser increases in remote locations where the air has remained relatively clean.

In addition to heat-trapping gases, human activities also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfate particles reflect incoming sunlight away from the Earth, exerting a cooling influence on Earth's surface. Another type of particle, soot or black carbon, absorbs incoming sunlight and traps heat in the atmosphere, warming the Earth.

In addition to their direct effects, these particles can affect climate indirectly by changing the properties of clouds. Some encourage cloud formation because they are ideal surfaces on which water vapor can condense to form cloud droplets. Some can also increase the number and decrease the average size of cloud droplets when there is not enough water vapor compared to the number of particles available. This creates brighter clouds that reflect away energy from the Sun, resulting in an overall cooling effect. Particles that absorb energy encourage cloud droplets to evaporate by warming the atmosphere. Depending on their type, particles can either counteract or increase the warming caused by increasing levels of greenhouse gases. At the scale of the planet, the net effect of these particles is to offset between 20% and 35% of the warming caused by heat-trapping gases.

The effects of all of these greenhouse gases and particles on the Earth's climate depend in part on how long these gases and particles remain in the atmosphere. Human-induced emissions of carbon dioxide have already altered atmospheric levels in ways that will persist for thousands of years. After a hundred years, about one third of the carbon dioxide emitted is still in the atmosphere. Methane lasts for approximately a decade before it is removed through chemical reactions. Particles, on the other hand, remain in the atmosphere anywhere from a few days to several weeks. This means that the effects of any human actions to reduce particle emissions can be seen nearly immediately. It may take decades, however, before the results of human actions to reduce long-lived greenhouse gas emissions can be observed. Some recent studies (Shindell et al. 2012) examine various means for reducing near-term changes in climate, for example, by reducing emissions of methane and black carbon (soot).

In addition to emissions of greenhouse gases, air pollutants, and particles, human activities have also affected climate by changing the land surface. These types of changes include cutting and burning forests, replacing natural vegetation with agriculture or cities, and large-scale irrigation. These transformations of the land surface can alter how much heat is reflected or absorbed by the surface, causing local and even regional warming or cooling. Globally, the net effect of these changes has probably been a slight cooling influence over the past 100 years.

Considering all known natural and human drivers of climate since 1750, a strong net warming from long-lived greenhouse gases produced by human activities dominates the recent climate record. This warming was partially offset by increases in atmospheric particles and their effects on clouds. Two important natural external drivers also influence climate: the Sun and volcanic eruptions. Since 1750, these natural external drivers have had a net warming influence, but one that is much smaller than the human influence. Natural internal drivers of climate, such as El Niño events in the Pacific Ocean, have also influenced regional and global climate. Many other modes of internal natural variability have been identified, and their effects on climate are superimposed on the effects of human activities, the Sun, and volcanoes.

During the last three decades, the Sun's energy output has decreased slightly. The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting 2 to 3 years. These natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has been a slight cooling influence over this period. In addition, the changes occurring now are very rapid compared to the major changes in climate over at least the last several thousand years. The magnitude of the human influence on climate and the rate of change raise concerns about the ability of ecosystems and human systems to successfully adapt to future changes.

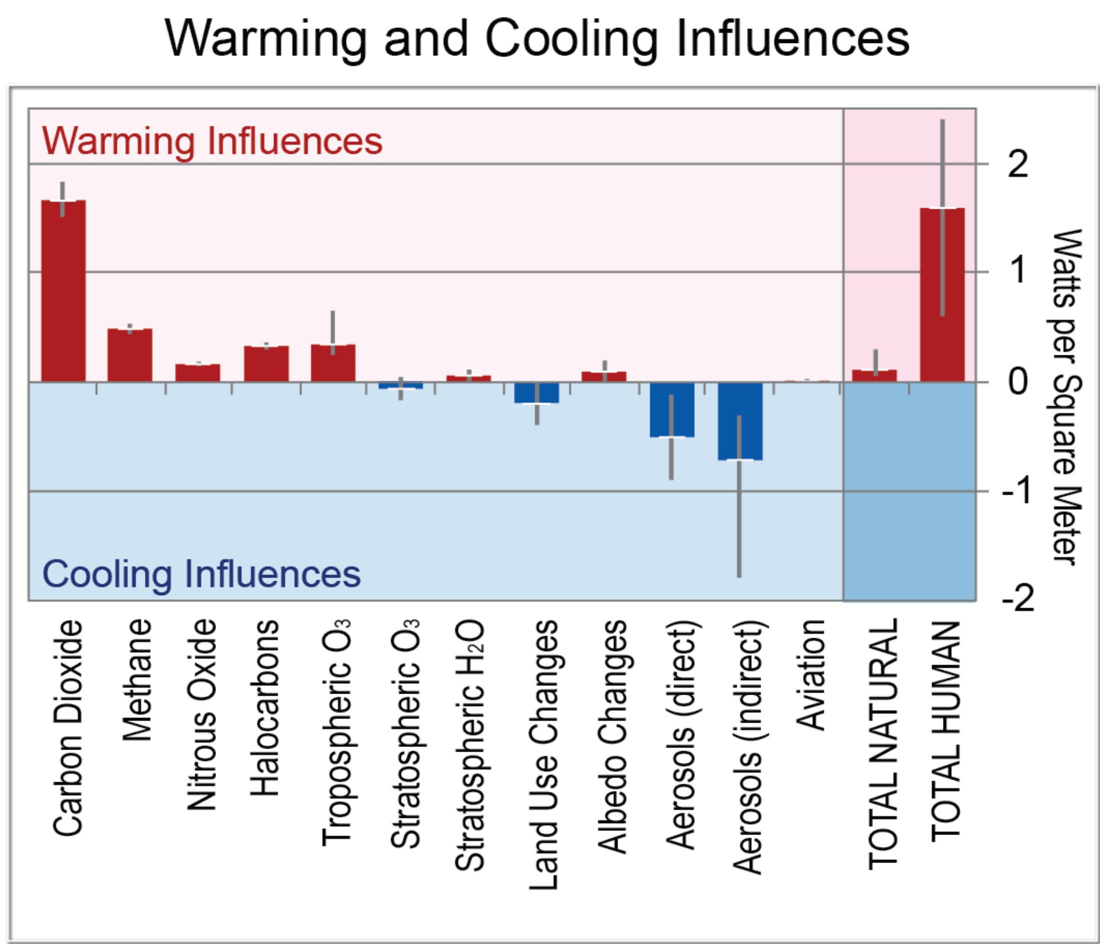

Figure 5: Warming and Cooling Influences

Caption: Different factors have exerted a warming influence (red bars) or a cooling influence (blue bars) on the planet. The warming or cooling influence of each factor is measured in terms of the increase in radiative forcing in watts per square meter by 2005 relative to 1750. This figure includes all the major human-induced factors as well as the Sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural, but is relatively short-lived so is not included here. The net effect is a strong warming, primarily from human activities. The thin lines on each bar show the range of uncertainty. (Forster 2007).

Key Message 2.

Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.

There are many types of observations that can be used to assess changes in climate. Thermometer and other instrument-based surface weather records date back hundreds of years in some locations. Air temperatures are measured at fixed locations over land and with a mix of predominantly ship- and buoy-based measurements over the ocean. By 1850, enough of these had accumulated to begin tracking global average temperature. Measurements from weather balloons began in the early 1900s, and by 1958 were regularly taken around the world. Satellite records beginning in the 1970s provide additional perspectives, particularly for remote areas such as the Arctic that have limited ground-based observations. Satellites also provided new capabilities for mapping precipitation and upper air temperatures, subject to uncertainties inherent in algorithms and instrument calibrations. Climate "proxies" are biological or physical records ranging from tree rings to ice cores that correlate with aspects of climate, providing evidence that can stretch back to hundreds of thousands of years.

Development of Observing Capabilities

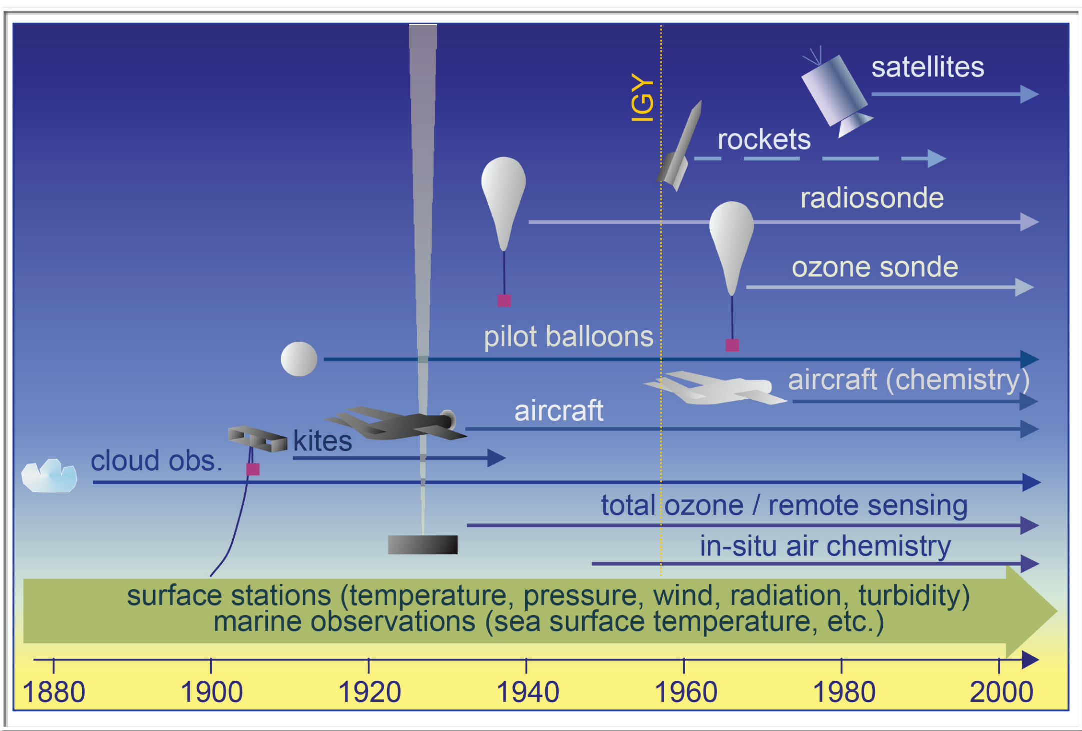

Figure 6: Development of Observing Capabilities

Caption: Changes in the mix and increasing diversity of technologies used to observe climate (IGY is the International Geophysical Year). (Adapted from Brönnimann et al. 2007).

These diverse data have been analyzed by scientists and engineers from research teams around the world in many different ways. The most high profile indication of the changing climate is the surface temperature record, so it has received the most attention. Spatial coverage, equipment, methods of observation, and many other aspects of the measurement record have changed over time, so scientists identify and adjust for these changes. Independent research groups have looked at the surface temperature record for land (Jones et al. 2012; Lawrimore et al. 2011; Rohde et al. 2012) and ocean (Kennedy et al. 2011; Smith and Reynolds 2002) as well as combined (Hansen et al. 2010; Morice 2012; Vose 2012). Each group takes a different approach, yet all agree that it is unequivocal that the planet is warming.

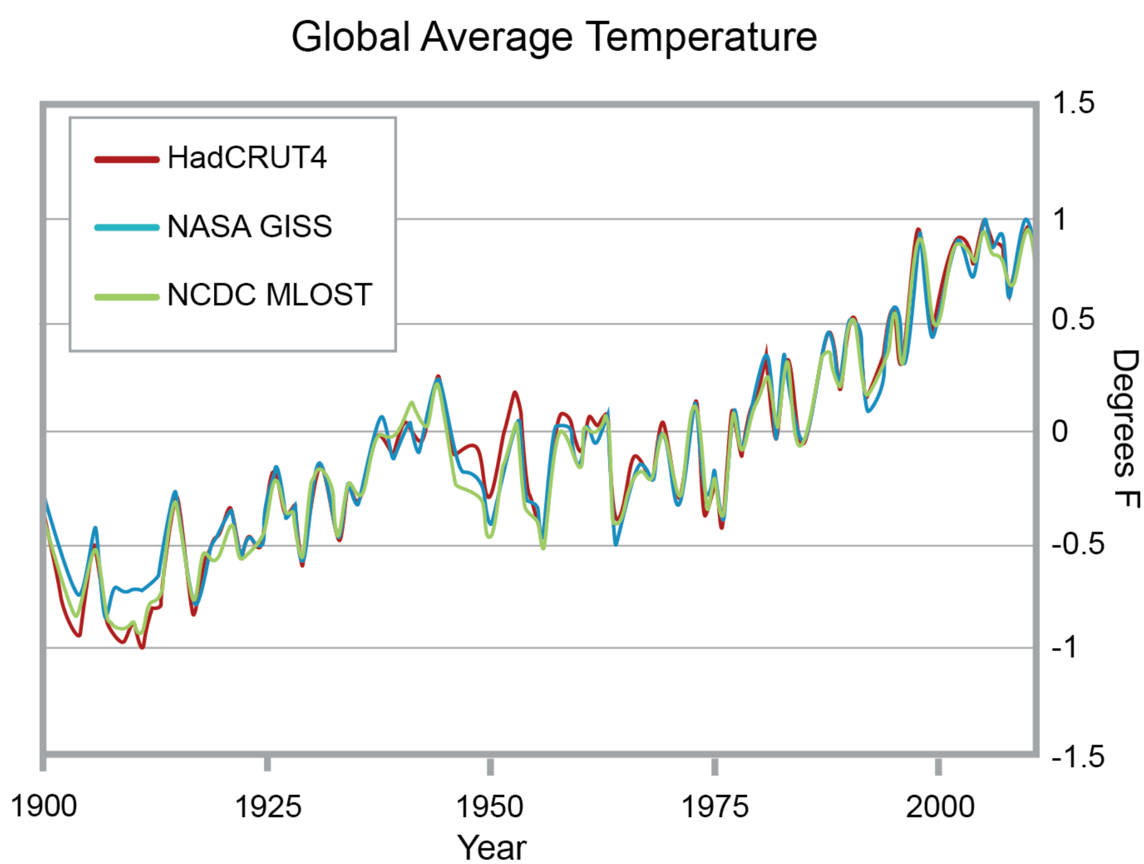

Figure 7: Global Average Temperature

Caption: Three different global surface temperature records all show increasing trends over the last century. The lines show annual average temperatures relative to the 1961-1990 average. Differences between the records, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Hansen et al. 2010; Morice 2012; Vose 2012)

There has been widespread warming over the past century. Not every region has warmed at the same pace, however, and a few regions, such as the North Atlantic Ocean and some parts of the U.S. Southeast, have even experienced cooling over the last century as a whole, though they have warmed over recent decades. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming, particularly at high northern latitudes, and over land as compared to ocean.

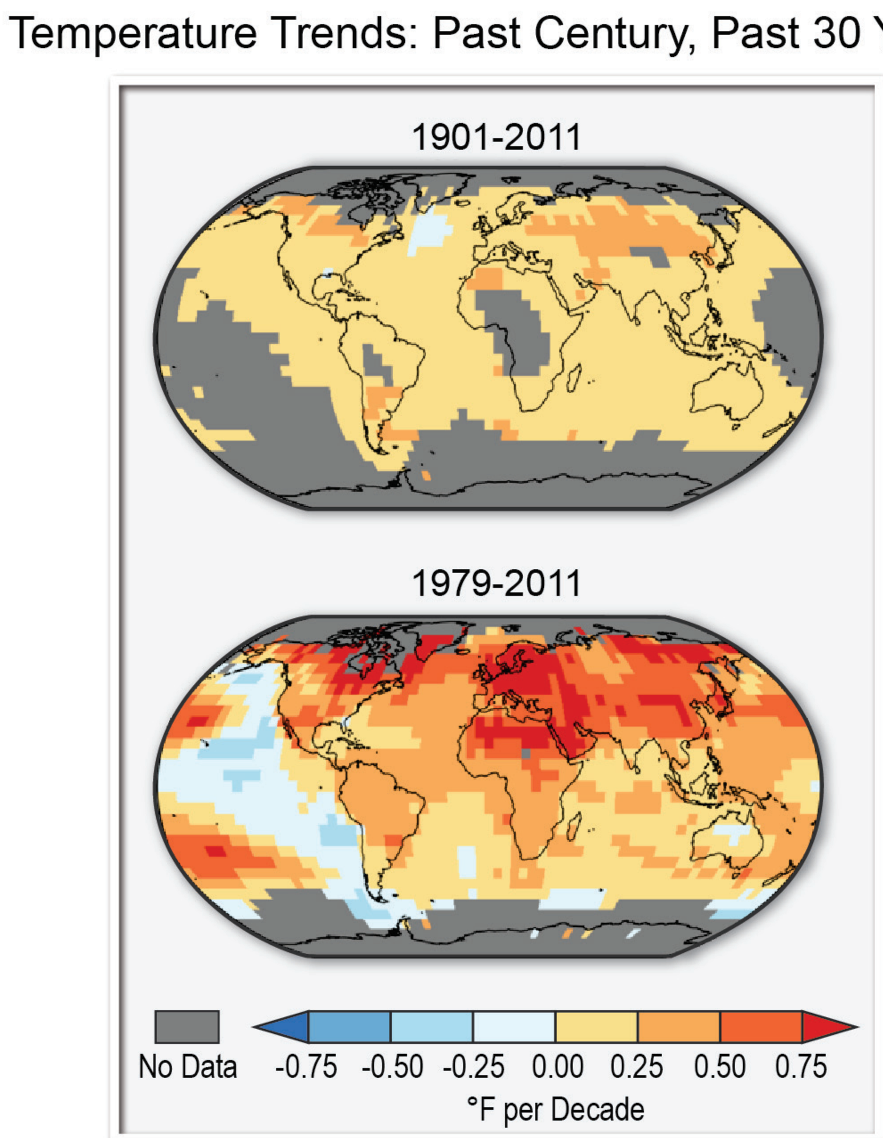

Figure 8: Temperature Trends: Past Century, Past 30 Years

Caption: Surface temperature trends for the period 1901-2011 (top) and 1979-2011 (bottom) from NCDC's surface temperature product (Vose 2012) .

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been rising because multiple lines of evidence all support this conclusion. Temperatures in the lower atmosphere and oceans have increased. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. Sea level and near-surface humidity have increased. As with temperature, multiple research groups have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming world.

Ten Indicators of a Warming World

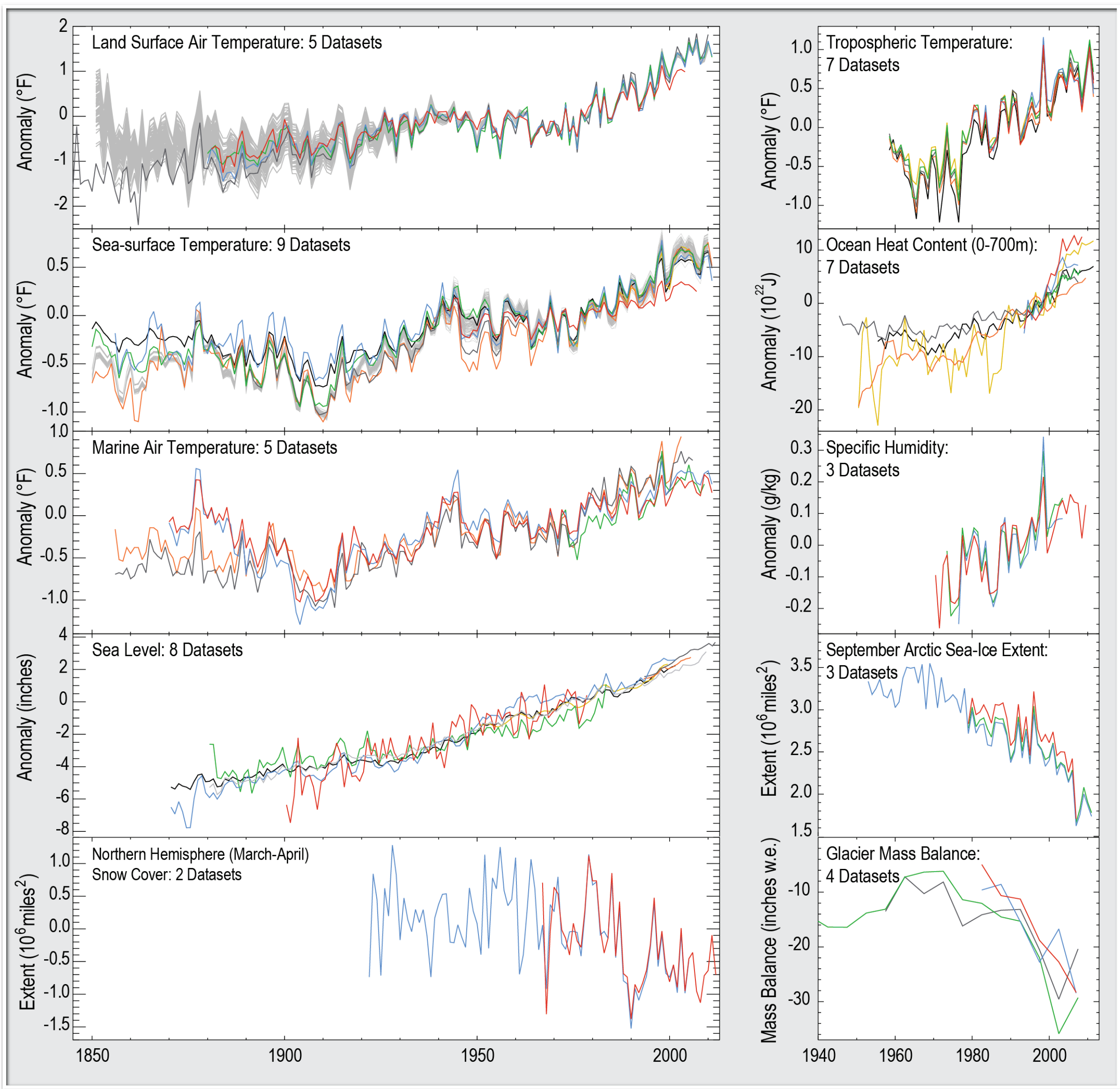

Figure 9: Ten Indicators of a Warming World

Caption: Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing in the ways that would be expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. Updated from (Kennedy et al. 2010).

Not all of the observed changes are directly related to temperature; some are related to the hydrological cycle. For example, there has been a slight increase in global average precipitation since 1900. However, there are strong geographic variations in this trend. In general, wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to warming.

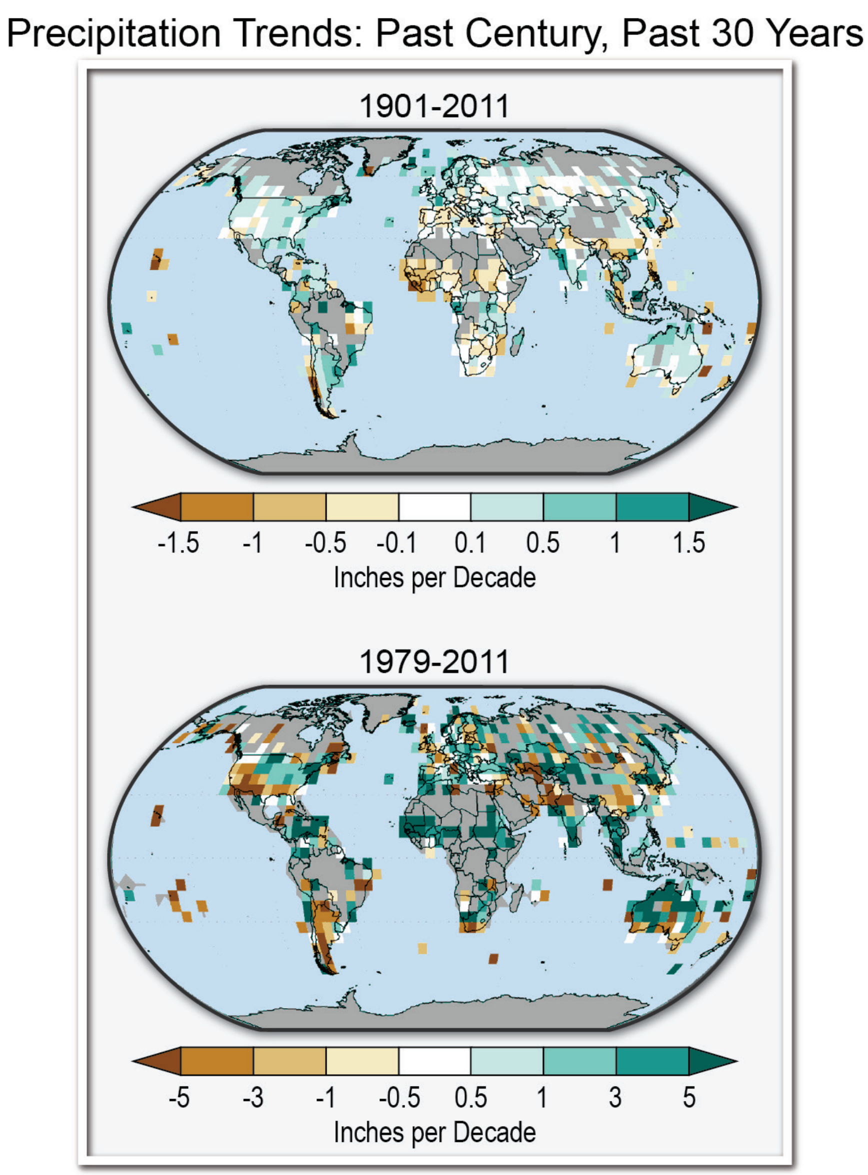

Figure 10: Precipitation Trends: Past Century, Past 30 Years

Caption: Global precipitation trends (inches per decade) for the period 1901-2011 (top) and 1979-2011 (bottom). (Figure source: NOAA NCDC)

Paleoclimate records based on climate proxies reveal that temperatures in the past have varied by about +/– 0.9°F over decadal time scales. Some periods in the past have been warmer, and others, cooler. However, the warming of the past 100 years is unusual relative to at least the past 2,000 years. Annual average global temperature during recent decades is at least as warm as the warmest interval of the past millennium globally, and continues to increase.

Key Message 3.

Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global temperature and precipitation over timescales ranging from months up to a decade or more.

Today, average temperature, precipitation, and other aspects of climate are determined by a combination of human-induced changes and natural variations. The relative magnitudes of the human and natural contributions to temperature and climate depend on both the time and spatial scales considered. The magnitude of the effect humans are having on global temperature specifically, and on climate in general, has been steadily increasing since the Industrial Revolution. At the global scale, however, the human influence on climate can be either masked or augmented by natural variations over timescales of a decade or so. At regional and local scales, natural variations have an even larger effect.

Natural variations can drive increases or decreases in global and regional temperatures, as well as affect precipitation and drought patterns around the world. Over the long term (the past 10,000 to 30,000 years), however, the influence of internal natural variability on the Earth's climate system is negligible; in other words, over multiple decades the net effect of natural variability tends to sum to zero.

There are many modes of natural variability in the climate system. Most of them involve cyclical exchanges of heat and energy between the ocean and atmosphere and are manifested by recurring changes in sea surface temperatures, for example, or by surface pressure changes in the atmosphere. The largest and most well known of these is the El Niño/Southern Oscillation or ENSO. This natural mode of variability was first identified as a warm current of ocean water off the coast of Peru and a shift in pressure between two locations on either side of the Pacific Ocean.

Although centered in the tropical Pacific, ENSO affects regional temperatures and precipitation around the world. In the United States, for example, the warm ENSO phase (commonly referred to as El Niño) is usually associated with heavy rainfall and flooding in California and the Southwest, but decreased precipitation in the Pacific Northwest. El Niño conditions also tend to suppress Atlantic hurricane formation by increasing the amount of wind shear in the region where hurricanes form. The cool ENSO phase (usually called La Niña) is associated with dry conditions in the Central Plains, as well as a more active Atlantic hurricane season. Although these and other conditions are typically associated with ENSO, no two ENSO events are exactly alike.

Natural variability such as ENSO can also affect global temperatures. In general, El Niño years tend to be warmer than average and La Niña, cooler. The strongest El Niño event recorded over the last hundred years occurred in 1998. Superimposed on the long-term increase in global temperatures due to human activities, this event caused record high global temperatures. After 1998, the El Niño event subsided, resulting in a nearly flat overall trend for the decade 1998-2007. Climate models can project the statistical behavior of these variations in temperature trends, but do not predict the exact timing of ENSO or other natural variations far into the future.

Natural modes of variability like ENSO are not necessarily stationary. For example, there appears to have been a shift in the pattern of ENSO in the mid-1970s, with the location of the warm water pool shifting from the eastern to the central Pacific. The frequency of natural variability can also change over time. Paleoclimate studies using tree rings show that ENSO activity over the last 100 years has been the highest in the last 500 years (Fowler et al. 2012) and both paleoclimate and modeling studies suggest that global temperature increases may interact with natural variability in ways that are difficult to predict.

La Niña and El Niño Patterns

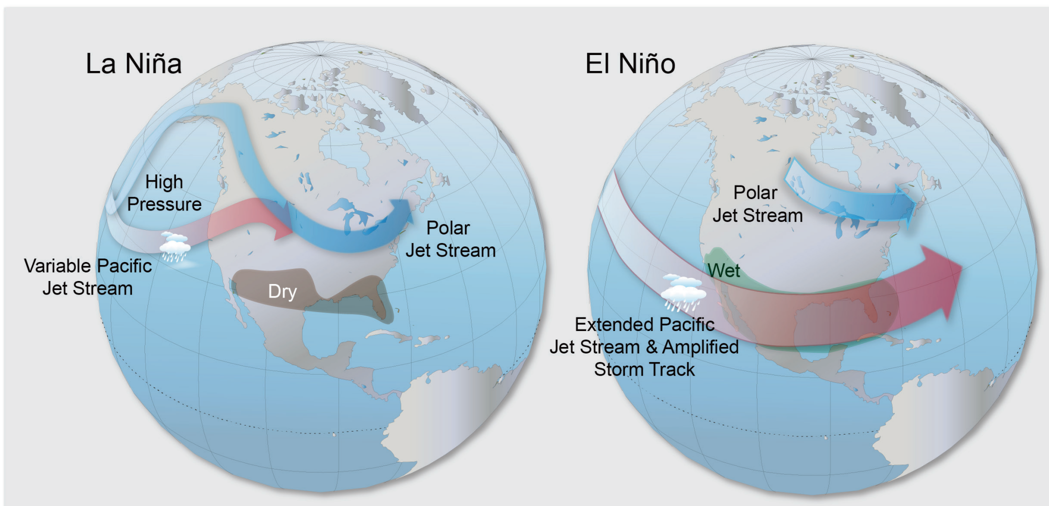

Figure 11: La Niña and El Niño Patterns

Caption: Typical January-March weather conditions and atmospheric circulation during El Niño events leads to unusually warm winter conditions in the northern U.S. and wetter than average conditions across the southern U.S. During La Niña, winters tend to be unusually cold through Alaska and western Canada, and dry throughout the southern (Figure source: NOAA)

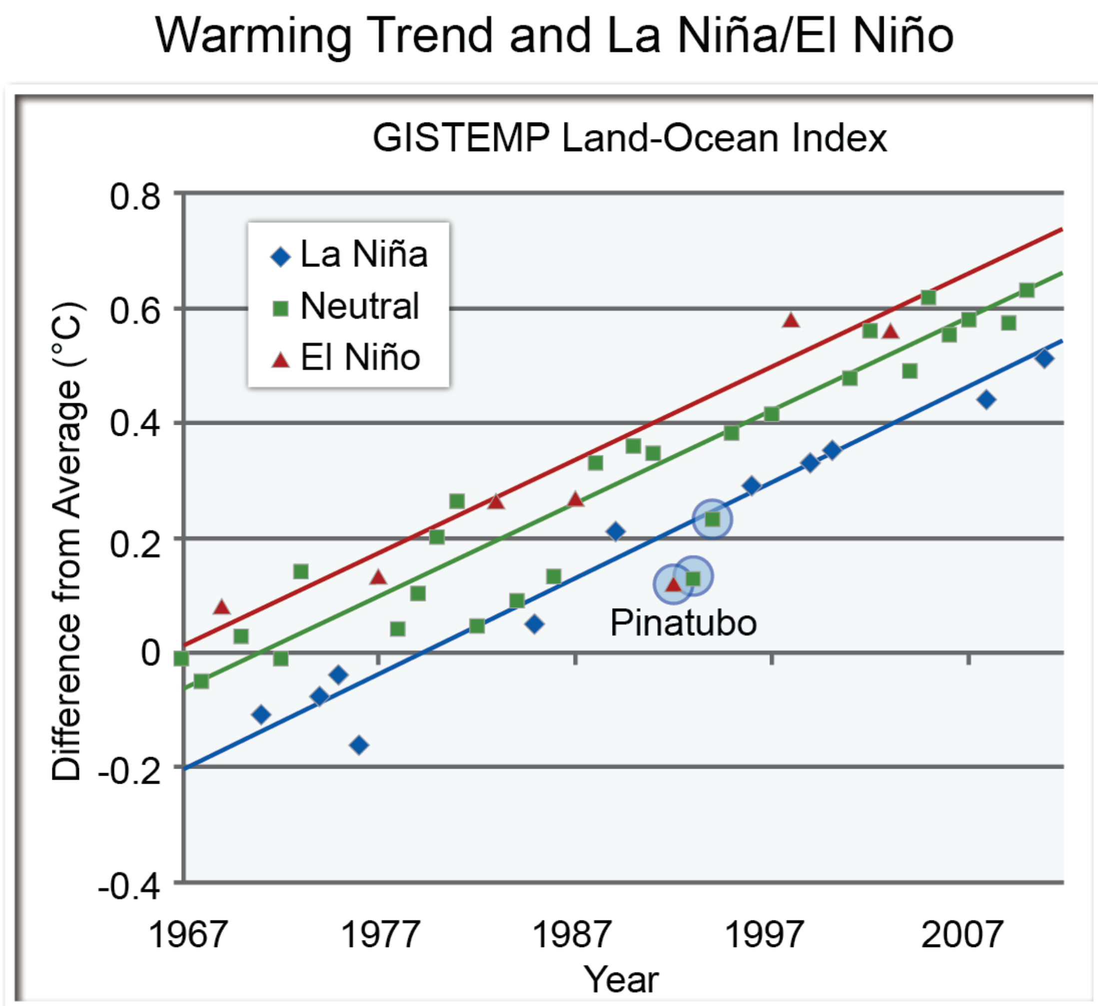

Figure 12: Warming Trend and El Niño/La Niña

Caption: Trends in globally and annually averaged temperature when considering whether it was an El Niño year, a La Niña year, or a neutral year (no ENSO event). When considering these sources of natural variability, all trends give the same significant increase in temperature over the past 45 years. The years for the short-term cooling effect following the Mt. Pinatubo volcanic eruption are not considered in the trends. Based on the NASA GISS temperature dataset (Morice 2012)

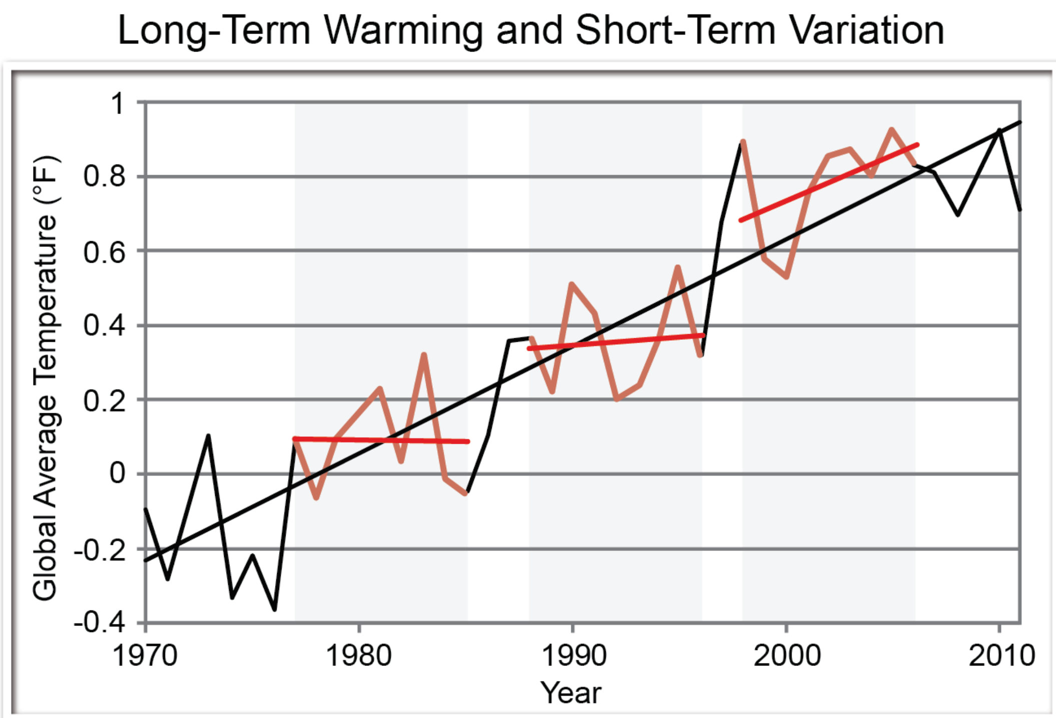

Figure 13: Long-Term Warming and Short-Term Variation

Caption: Observations of global mean surface air temperature show that although there can be short periods with little or even no significant upward trend (see for example the red trend lines in shaded areas for the periods 1977-1985, 1989-1996, and 1998-2006), global temperature continues to rise unabated over long-term climate timescales (black trend line). Source:

There are other natural modes of variability in the climate system. For example, the North Atlantic Oscillation is frequently linked to variations in winter snowfall along the Atlantic seaboard. The Pacific Decadal Oscillation was first identified as a result of its effect on the Pacific salmon harvest. The influence of these and other natural variations on global temperatures is generally less than ENSO, but local influences may be large.

A combination of natural and human factors explains regional "warming holes" where temperatures actually decreased for several decades in the middle to late part of the last century at a few locations around the world. In the U.S., for example, the Southeast and parts of the Great Plains and Midwest regions don't show much warming over that time period, though they have warmed in recent decades. Explanations include increased cloud cover and precipitation (Pan et al. 2004), increased small particles from coal burning, and natural factors related to forest re-growth (Portmann et al. 2009), decreased heat flux due to irrigation (Puma and Cook 2010), and multi-decade variability in North Atlantic and tropical Pacific sea surface temperatures (Kunkel et al. 2006; Meehl et al. 2012; Robinson et al. 2002).

The importance of tropical Pacific and Atlantic sea surface temperatures on temperature and precipitation variability over the central U.S. has been particularly highlighted by many studies.

Over the next few decades, as the multi decadal tropical Pacific Ocean cycle continues its effect on sea surface temperatures, the U.S. Southeast could warm at a rate that is faster than the global average (Meehl et al. 2012). At the global scale, natural variability will continue to modify the long-term trend in global temperature due to human activities, resulting in greater and lesser trends over relatively short time scales. Global climate models simulate natural variability with varying degrees of realism, but the timing of these random variations differs among models and cannot be expected to coincide with those of the actual climate system. Averaging (or compositing) of projections from different models smooths out the randomly occurring natural variations in the different models, leaving the signal of the externally forced changes.

Key Message 4.

Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.

Determining the causes of climate changes is a field of research known as "detection and attribution." *Detection* involves identifying a climate trend or event (for instance, long-term surface air temperature trends, or a particularly extreme heat wave) that is strikingly outside the norm, including natural variations in the climate system. Similar to conducting forensic analysis on evidence from a crime scene, *attribution* involves considering the possible causes of an observed event or change, and identifying which is responsible for the observed behavior.

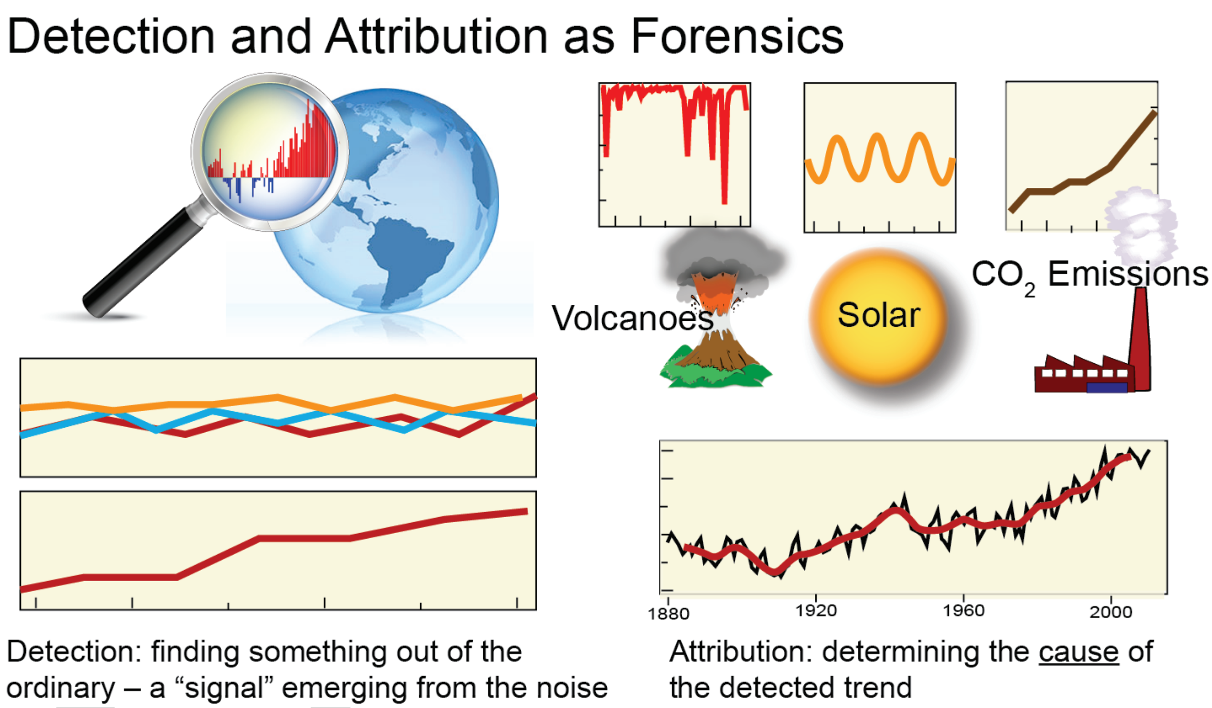

Figure 14: Detection and Attribution as Forensics

Caption: Detection and attribution of climate changes. The natural factors considered usually include changes in the Sun's output and volcanic eruptions, as well as natural modes of variability such as El Niño and La Niña. Human factors include the emissions of heat-trapping gases and particulates as well as clearing of forests and other land-use changes. (Figure source: NOAA NCDC)

Detection and attribution studies use statistical analyses to identify the causes of observed behavior. They do this by trying to match the complex "fingerprint" of the observed climate system behavior to a set of simulated changes in climate that would be caused by different drivers (Stott et al. 2010). Most approaches consider changes in geographical patterns over time.

Climate simulations are used to test hypotheses regarding the causes of observed changes. First, simulations that include changes in both external natural and human drivers that may cause climate changes, such as increases in heat-trapping gases and changes in energy from the Sun, are used to characterize what effect those factors would have had. Then, simulations with no changes in external drivers, only changes in natural variability, are used to characterize what would be expected from normal internal variations in the climate.

Detection and attribution studies have been applied to a broad range of elements of the climate system and a number of specific extreme events that have occurred in recent years. Many published scientific studies have found that human influences are required to explain the observed changes in climate over the last half century. These changes include increases in surface temperatures (Jones and Stott 2011; Stott et al. 2010), changes in atmospheric vertical temperature profiles (Lott et al. 2012; Santer 2012), increases in ocean heat content (AchutaRao et al. 2007; AchutaRao et al. 2006), increasing atmospheric humidity (Santer et al. 2007; Willett et al. 2007), increases in intensity of precipitation (Min et al. 2011) and in runoff (Gedney et al. 2006), indirectly estimated through changes in ocean salinity (Durack et al. 2012), shifts in atmospheric circulation (Gillett and Stott 2009) and changes in a host of other indices (Stott et al. 2010). Taken together these paint a coherent picture of a planet whose climate is changing primarily as a result of human activities.

Human Influences Apparent in Many Climate Variables

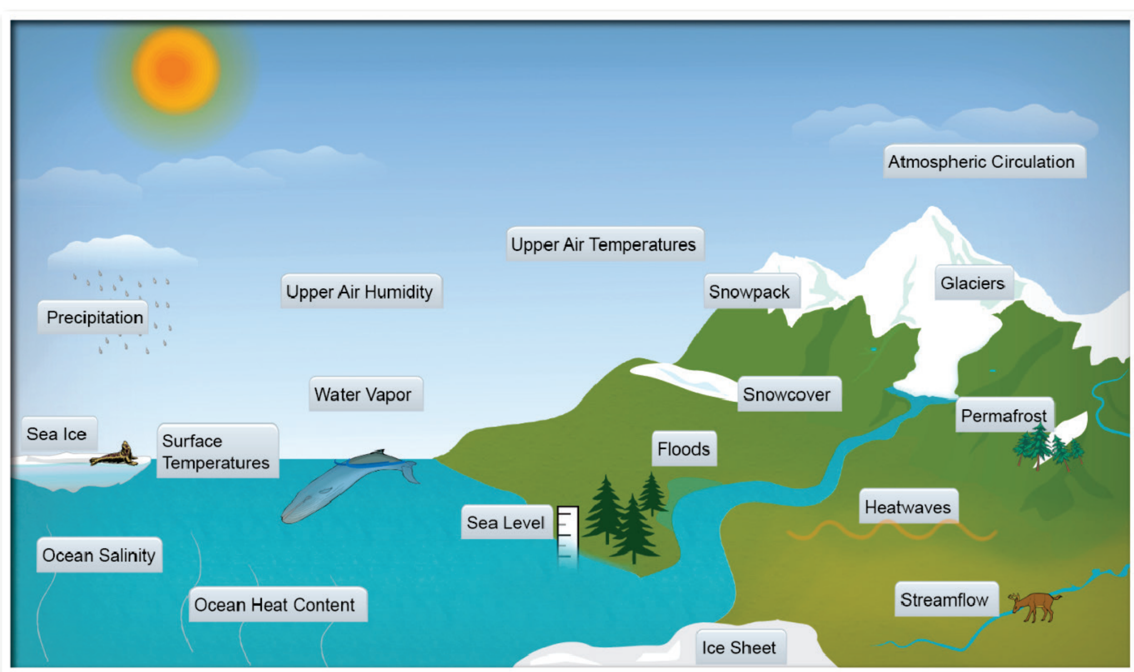

Figure 15: Human Influences Apparent in Many Climate Variables

Caption: Long-term trends and changes in extreme events are apparent for many aspects of the climate system. Scientific analyses can determine the extent to which these changes are attributable to human influences. (Figure source: NOAA NCDC)

Only Human Influence Can Explain Recent Warming

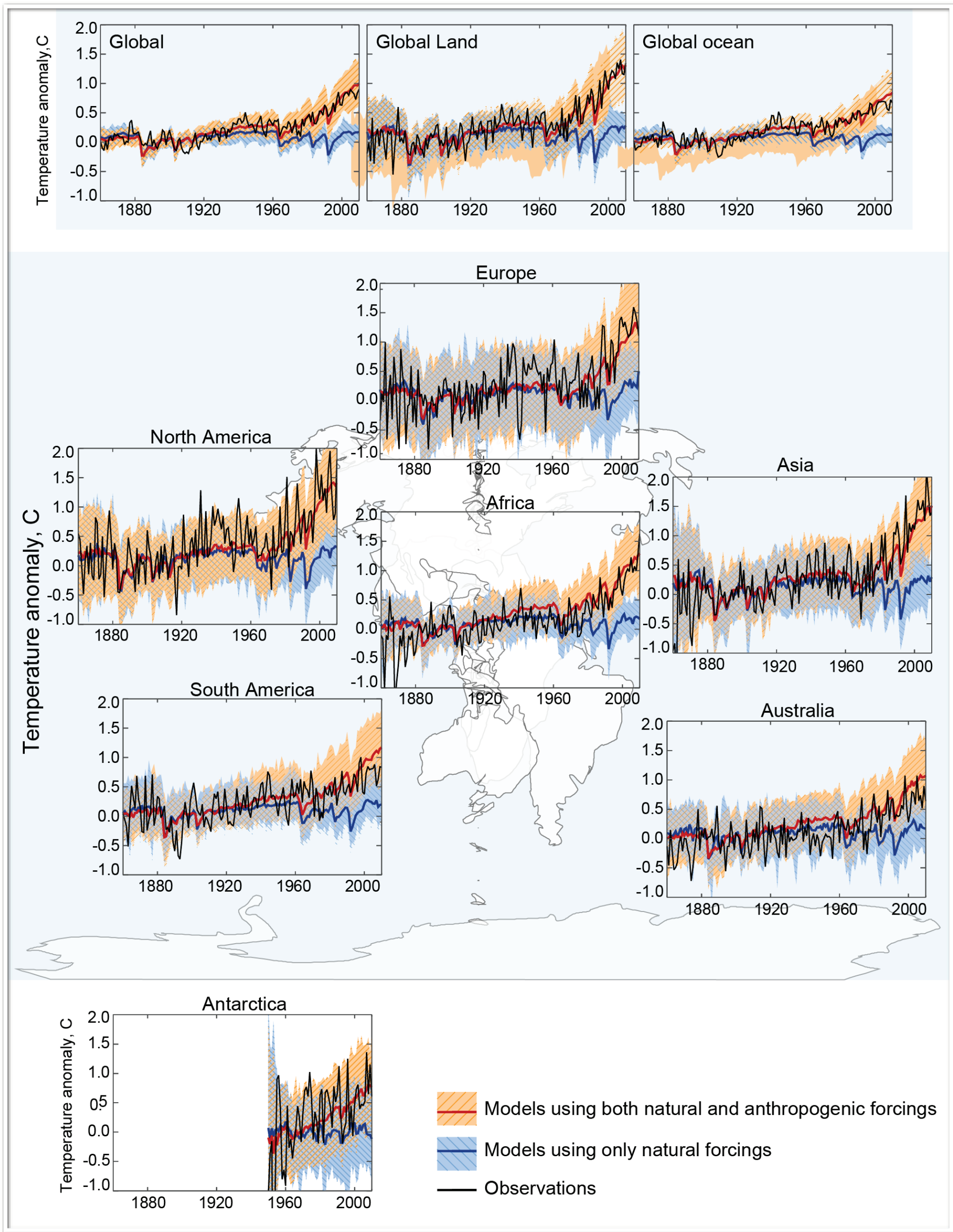

Figure 16: Only Human Influence Can Explain Recent Warming

Caption: Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the observed changes in ten-year averages. The blue shading represents estimates from a broad range of climate simulations including solely natural (solar and volcanic) changes. The pink shading shows simulations including both the natural and human contributions. (Figure source: Jones et al. submitted)

Detection and attribution of specific events is more challenging than for long-term trends as there is less data, or evidence, available from which to draw conclusions. Attribution of extreme events is especially scientifically challenging (Allen 2011; Curry 2011; Trenberth 2011). Many extreme weather and climate events observed to date are within the range of what could have occurred naturally, but, the probability, or odds, of some of these very rare events occurring (Stott et al. 2011; Stott 2011) has been significantly altered by human influences on the climate system. Studies have concluded that there is a detectable human influence in recent heat waves in Europe (Christidis et al. 2012; Stott et al. 2004), Russia (Dole et al. 2011; Otto et al. 2012; Rahmstorf and Coumou 2011), and Texas (Hoerling et al. 2012 (submitted)) as well as flooding events in England and Wales (Pall et al. 2011), the timing and magnitude of snowmelt and resulting stream flow in some Western U.S. states (Barnett et al. 2008; Hidalgo et al. 2009; Pierce et al. 2008), and some specific events around the globe during 2011 (Peterson et al. 2012).

Key Message 5.

Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.

A certain amount of climate change is already inevitable due to the build-up of CO_2 in the atmosphere from human activities over the past few centuries. Even if the net CO_2 emissions could be reduced to zero today, the human-induced perturbation to the global carbon cycle would persist for thousands of years (NRC 2011). Because global emissions of CO_2 and other heat-trapping gases continue to rise, exactly how much climate will change over this century and beyond depends primarily on two factors: 1) the amount of human activities and resulting emissions; and 2) how sensitive the climate is to those changes (the responsiveness of temperature to a change in radiative forcing).

Uncertainties in how the economy will evolve, where we'll be getting our energy from, or what our cities, our buildings, or our cars will look like, affect our ability to predict the future changes in climate. However, a series of plausible projections of what might happen, under a given set of assumptions, can and have been developed. These scenarios describe the future in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

Some amount of future change is already inevitable due to past emissions of heat-trapping gases. The Earth's climate system, particularly the ocean, tends to lag the change in net incoming radiation by decades, and even centuries, in responding to changes in atmospheric composition. Even if all emissions of heat-trapping gases from human activity were suddenly stopped, a temperature increase of 0.5°F increase would occur (Matthews and Zickfeld 2012).

Over the next few decades, the greater part of the range in projected global and regional change is the result of natural variability and scientific limitations in our ability to model and understand the Earth's climate system. By the second half of the century, however, emissions scenario uncertainty (in other words, the net effect of human activities on the climate system) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects (Hawkins and Sutton 2009, 2011). Even though natural variability will still occur in the future, the majority of the difference between the future and present climates will be determined by choices that human society is making today and over the next few decades. The further out in time we look, the greater the influence of human choices on the magnitude of future change.

For temperature, it is clear that increasing emissions from human activities will drive consistent increases in global and even most regional temperatures and that these rising temperatures will increase with the magnitude of future emissions (see Figure 17 below and Figures 2.7 and 2.8 in Ch. 2: Our Changing Climate). Uncertainty in projected temperature change is generally smaller than uncertainty in projected changes in precipitation or other aspects of climate; however, these are also projected to change as a result of the impacts of human activities on global climate.

Future climate change also depends on climate sensitivity**,** generally summarized as the response of global temperature to a doubling of CO_2 levels in the atmosphere relative to pre-industrial levels of 280 parts per million. If the only result of increasing atmospheric CO_2 levels were to amplify the natural greenhouse effect (as CO_2 levels increase, more of the Earth's heat is absorbed by the atmosphere before it can escape to space) it would be relatively easy to calculate the change in global temperature that would result from a given increase in CO_2 levels. But a series of natural feedbacks within the Earth system act to amplify or diminish an initial change, adding uncertainty to the climate sensitivity. Some important feedbacks include:

- Clouds – Will warming increase or decrease cloudiness? Will the changes be to clouds that primarily reflect the Sun's energy, or clouds that trap even more heat within the Earth system?
- Albedo – How quickly will bright white reflective surfaces, such as snow and ice, that reflect most of the Sun's energy, melt, and be replaced by a dark ocean or land area that absorbs most of the Sun's energy?
- Carbon dioxide uptake by the ocean and the biosphere – Will the rate of uptake increase in the future, helping to remove human emissions from the atmosphere? Or will it decrease, causing emissions to build up even faster than they are now?

Together, these and other feedbacks determine the long-term response of the Earth's temperature to an increase in carbon dioxide and other emissions from human activities.

Past observations, including both recent measurements as well as studies that look at climate changes in the distant past, can't tell us precisely how sensitive the climate system will be to increasing emissions of heat-trapping gases if we are starting from today's conditions. They can tell us, however, that the net effect of these feedbacks will be to increase, not diminish, the direct warming effect. In other words, the climate system will warm by more than would be predicted from the greenhouse effect alone.

From a large number of independent datasets and analyses, it appears that the best estimate of climate sensitivity is about 5.4ºF (3ºC), with a likely range from 3.5ºF to 8ºF (for a doubling of the CO_2 concentration from preindustrial levels). This sensitivity includes feedbacks that respond to global temperature change over timescales of years to decades. These "fast" feedbacks include increases in atmospheric water vapor, reduction of ice and snow, warming of surface ocean temperature, and changes in cloud characteristics. The entire response of the climate system will not be seen until the deep ocean comes into balance with the atmosphere, a process that can take thousands of years.

Combining the uncertainty due to climate sensitivity with the uncertainty due to human activities produces a range of future temperature changes that overlap over the first half of this century, but begins to separate over the second half of the century as atmospheric CO_2 levels diverge.

As discussed previously in Key Message 3, interactions among various components of the Earth's system produce patterns of natural variability that can be chaotic, meaning that they are sensitive to the initial conditions of the climate system. These patterns can affect global and regional climate on time scales ranging from years to a decade or more. Over climatological time periods, however, the net effect of natural internal variability on the global climate tends to average to zero. For example, there can be warmer years due to El Niño (such as 1998) and cooler years due to La Niña (such as 2011); but over multiple decades the net effect of natural variability on uncertainty in global temperature and precipitation projections is small. In this report, all future projections are averaged over 20- to 30-year time periods.

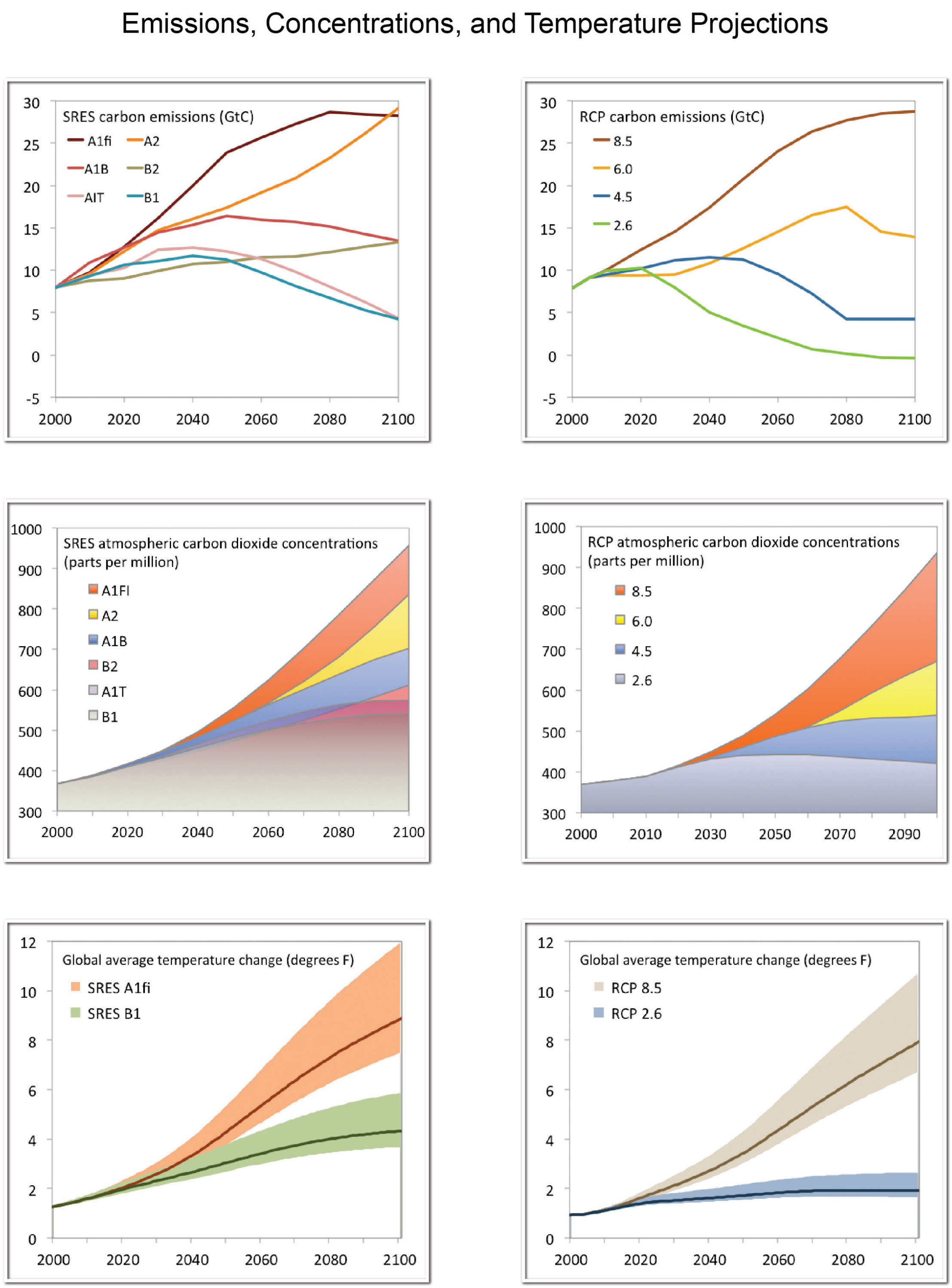

Figure 17: Emissions, Concentrations, and Temperature Projections

Caption: Two families of scenarios are commonly used for future climate projections: the 2000 Special Report on Emission Scenarios (SRES, left) and the 2010 Representative

Concentration Pathways (RCP, right). This figure compares SRES and RCP (top) annual carbon emissions (GtC), (middle) carbon dioxide equivalent levels in the atmosphere (ppm), and (bottom) resulting temperature change that would result from the best-guess (lines) and the likely range (shaded areas) of climate sensitivity (ºF). At the top end of the range, the older SRES scenarios are slightly higher. At the bottom end of the range, the RCP scenarios are much lower. This divergence is because RCP scenarios include the option of using policies to reduce carbon dioxide emissions, while SRES scenarios do not. (Data from CMIP3 and CMIP5)

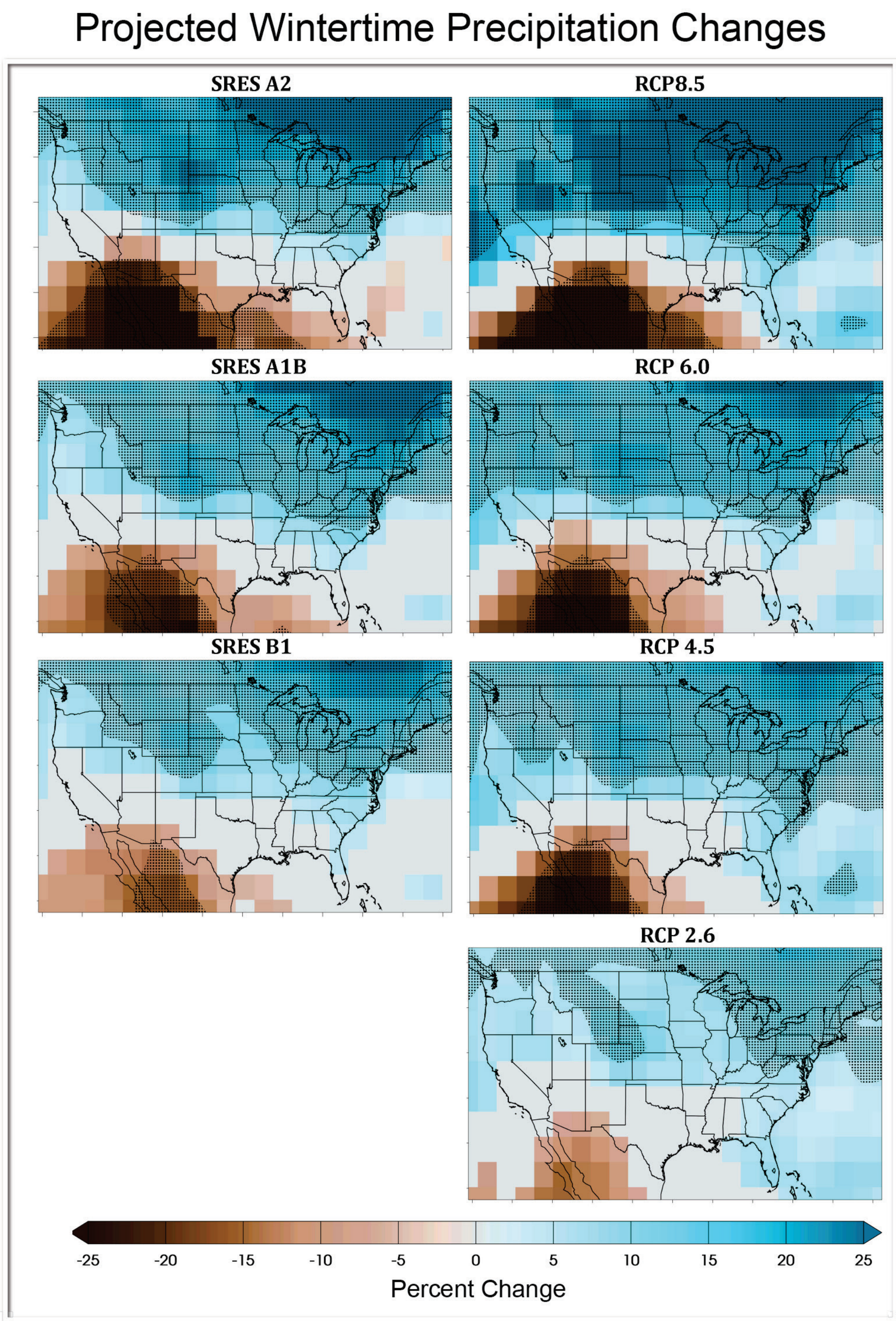

Figure 18: Projected Wintertime Precipitation Changes

Caption: Projected changes in wintertime precipitation at the end of this century (2071-2099) relative to the average for 1901-1960. The older generation of models (CMIP3) and emissions scenarios are on the left side, the new models (CMIP5) and scenarios are on the right side. Teal indicates precipitation increases, and brown, decreases. Stippled areas indicate confidence that the projected changes are large and are consistently wetter or drier. Gray areas indicate confidence that the changes are small. In both sets of projections, the northern parts of the U.S. (and Alaska) become wetter. Increases in both the amount of precipitation change and the confidence in the projection increase as the projected temperature increases. In the farthest northern parts of the U.S., much of the additional winter precipitation will still fall as snow. This is not likely to be the case farther south. Units: Percent. (Figure source: Michael Wehner, LBNL. Data from CMIP3 and CMIP5.).

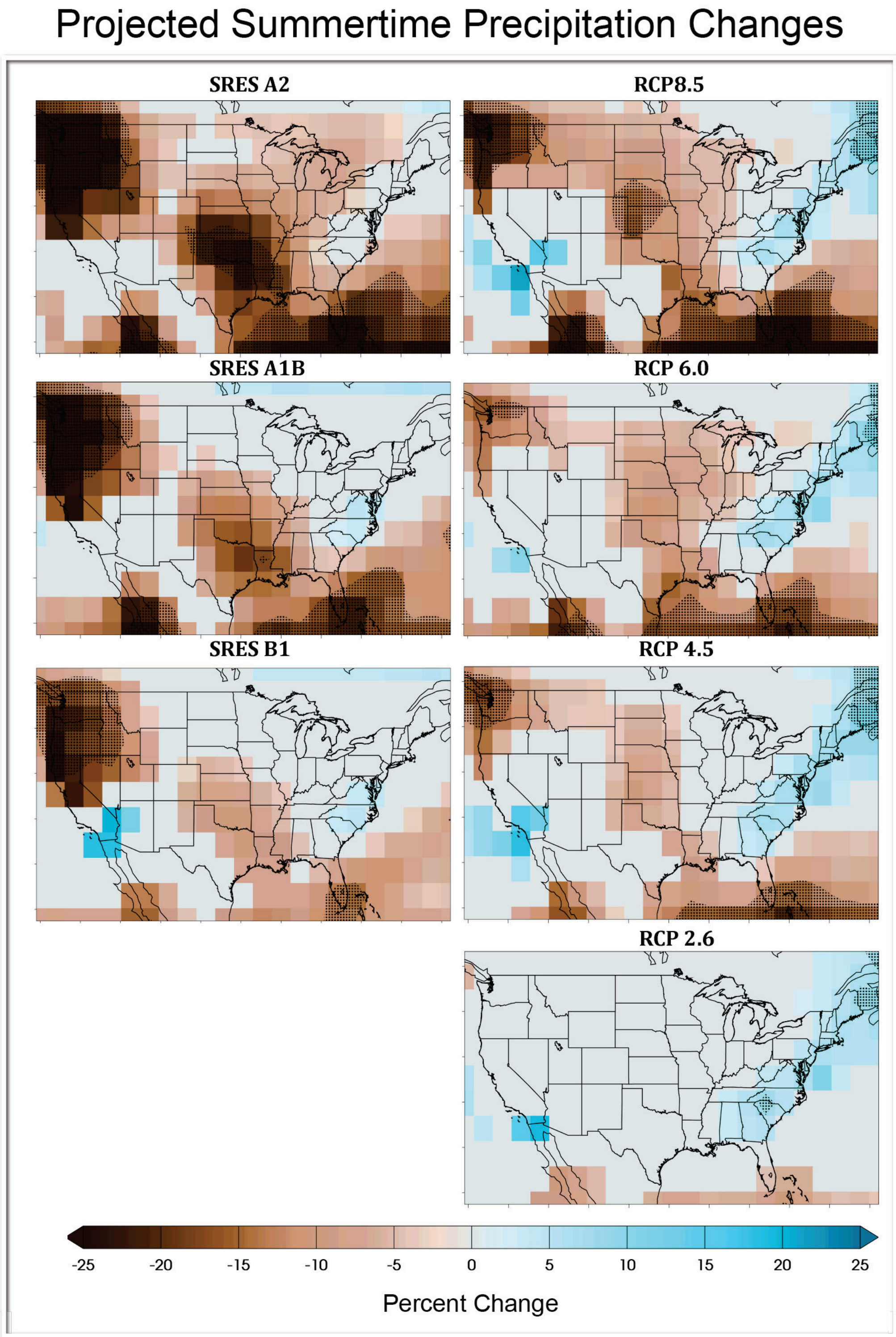

Figure 19: Projected Summertime Precipitation Changes

Caption: Projected changes in summertime precipitation at the end of this century (2071-2099) relative to the average for 1901-1960. The older generation of models (CMIP3) and emissions scenarios are on the left side, the new models (CMIP5) and scenarios are on the right side. Teal indicates precipitation increases, and brown, decreases. Stippled areas indicate confidence that the projected changes are large and are consistently wetter or drier. Gray areas indicate confidence that the changes are small. In most of the contiguous U.S., decreases in summer precipitation are projected, but not with as much confidence as the winter increases. When interpreting maps of temperature and precipitation projections, readers are advised to pay less attention to small details and greater attention to the large-scale patterns of change.((Figure source: Michael Wehner, LBNL. Data from CMIP3 and CMIP5.)

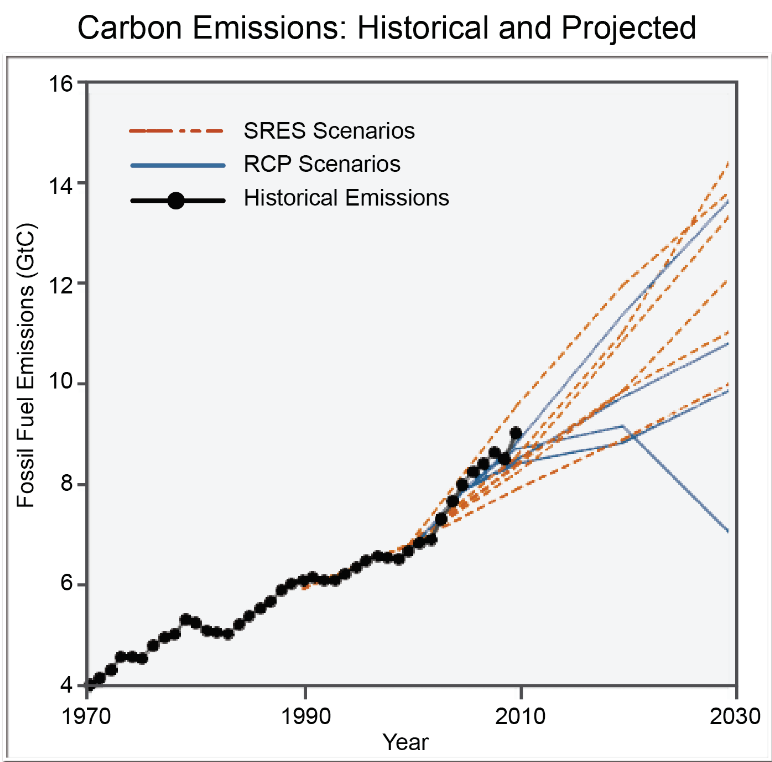

Figure 20: Carbon Emissions: Historical and Projected

Caption: Historical emissions of carbon from fossil fuel combustion and land-use change, including the combustion of coal, gas and oil and deforestation, have increased over time. The growth rate was nearly three times greater during the 2000s as compared to the 1990s. This figure compares the observed historical (black dots) and projected future SRES (orange dashed lines) and RCP (blue solid lines) carbon emissions from fossil fuel consumption from 1970 to 2030. Source:

Key Message 6.

Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging many models, many clear trends emerge.

Climate scientists cannot create laboratory conditions that represent all the complexity of the earth system for performing experiments. Instead,, they use a wide range of observational and computational tools to understand the complexity of the Earth's climate system and to study how that system responds to external forces, including the effect of humans on climate.

Computational tools include models that simulate different parts of the climate system. The most sophisticated computational tools used by climate scientists are **general circulation models** (also referred to as "global climate models"), or GCMs. GCMs are mathematical models that simulate the physics, chemistry and, increasingly, the biology that influence the climate system. These are physical models, which are not based on statistical correlations, such as an observed relationship between global temperature and carbon dioxide. Rather, global climate models are built on the immutable equations of physics. These fundamental equations include the conservation of energy, mass, and momentum and how these properties are exchanged between different parts of the climate system.

Using these fundamental relationships, GCMs are able to simulate many important features of the Earth's climate system: the Jet Stream that circles the globe 30,000 feet up in the atmosphere; the Gulf Stream and other ocean currents that transport heat from the tropics to the poles; and even, when the models can be run at a fine enough spatial resolution to capture these features, hurricanes in the Atlantic and typhoons in the Pacific. These processes are simulated directly from the laws of physics and do not require any assumptions derived from fitting to observations or other data.

GCMs and other physical models are subject to two main types of uncertainty. First, because full scientific understanding of the climate system is not complete, a model may not include an important process. This could be because that process is not yet known, or because it is known but is not yet understood well enough to be modeled accurately. For example, GCMs do not currently include adequate treatments of dynamical mechanisms that are important to melting ice sheets. The existence of these mechanisms is known, but they are not quite well enough understood yet to simulate accurately at the global scale. Observations of climate change in the distant past suggest there might be "tipping points" or mechanisms of abrupt changes in climate change that are not adequately understood.

Second, many processes occur in time and space at scales finer than models can resolve. Models instead must approximate what these processes would look like at the spatial scale that the model can resolve using empirical equations, or parameterizations, based on a combination of observations and science. These include small-scale physical processes such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere. For example, GCMs cannot model every single raindrop. However, they can simulate the total amount of rain that would fall over a large area the size of a grid cell in the model. These approximations are usually derived from a limited set of observations and/or higher resolution modeling and may not hold true for every location or under all possible conditions.

GCMs are constantly being enhanced as scientific understanding of climate improves and as computational power increases. For example, in 1990, the average GCM divided up the world into grid cells measuring more than 300 miles per side. Today, most GCMs divide the world up into grid cells of about 60 to 100 miles per side, and some of the most recent models are able to run short simulations with grid cells of only 15 miles per side.

Another way GCMs have improved is by incorporating more of the physical processes and components that make up the Earth's climate system. The very first global climate models were designed to simulate only the circulation of the atmosphere. Over time, the ocean, clouds, land surface, ice and snow, and other features were added one by one. Most of these features were new modules that were developed by experts in those fields and then added into an existing GCM framework. Today, there are more than 35 GCMs created and maintained by more than 20 modeling groups around the world. Some of the newest GCMs are what are known as earth system models, or ESMs. ESMs include all the previous components of a typical GCM, but also incorporate modules that represent additional aspects of the climate system, including agriculture, vegetation, and the carbon cycle.

Some models are more successful than others at reproducing observed climate and trends over the past century (Randall 2007). However, all future simulations agree that both global and regional temperatures will increase over the coming century in response to increasing emissions of heat-trapping gases from human activities (IPCC 2007).

Despite their increasing resolution, most GCMs cannot simulate fine-scale changes at the regional to local scale. For that reason, **downscaling** is often used to translate GCM projections into the high-resolution information required as input to impact analyses. There are two types of models commonly used for downscaling: dynamical and statistical.

Dynamical downscaling models are often referred to as regional climate models since they include many of the same physical processes that make up a global climate model, but simulate these processes at higher resolution and over a relatively small area, such as the Northwest or Southeast U.S. At their boundaries, regional climate models use output from GCMs to simulate what is going on in the rest of the world. Regional climate models are computationally intensive, but provide a broad range of output variables including atmospheric circulation, winds, cloudiness, and humidity at spatial scales ranging from about 6 up to 30 miles per grid cell. They are also subject to the same types of uncertainty as a global model: that of not including or correctly representing a physical process, as well as that of simulating processes that occur at smaller scales than the model can resolve. Regional climate models have additional uncertainty from how their boundaries are specified (frequency of updates and where they are defined). These uncertainties can have a large impact on the precipitation simulated by the models at the local to regional scale. Currently, a limited set of regional climate model simulations based on one future scenario and output from five GCMs is available from the North American Regional Climate Change Program. These simulations are useful for examining certain impacts of global change over North America. However, they do not encompass the full range of uncertainty in future projections due to both human activities and climate sensitivity described in Key Message 5.

Statistical downscaling models use observed relationships between large-scale weather features and local climate to translate future projections down to the scale of observations. Statistical models are based on a key assumption: that the relationship between large-scale weather systems and local climate will remain constant over time. This assumption may be valid for lesser amounts of change, but could lead to biases, particularly in precipitation extremes, with larger amounts of climate change (Vrac et al. 2007). Statistical models are generally flexible and less computationally demanding than regional climate models. A number of databases provide statistically downscaled projections for a continuous period from 1960 to 2100 using many global models and a range of higher and lower future scenarios. Hence, statistical downscaling models are best suited for analyses that require a range of future projections that reflect the uncertainty in emission scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes.

Ideally, climate impact studies could use both statistical and dynamical downscaling methods. Regional climate models can directly simulate the response of regional climate processes to global change, while statistical models can better remove any biases in simulations relative to observations. However, rarely (if ever) are the resources available to take this approach. Instead, most assessments tend to rely on one or the other type of downscaling, where the choice is based on the needs of the assessment. If the study is more of a sensitivity analysis, where using one or two future simulations is not a limitation, or if it requires many climate variables as input, then regional climate modeling may be more appropriate. If the study needs to resolve the full range of projected changes under multiple GCMs and scenarios, or is more constrained by practical resources, then statistical downscaling may be more appropriate. However, even within statistical downscaling, selecting an appropriate method for any given study depends on the questions being asked. The variety of techniques ranges from a simple delta approach (which consists of subtracting historical simulated values from future values, and adding the resulting “delta” to historical observations, as used in (NAST 2000) to complex clustering and neural network techniques that rival dynamical downscaling in their demand for computational resources and high-frequency GCM output (e.g., Kostopoulou and Jones 2007; Vrac et al. 2007). The delta approach is adequate for studies that are only interested in changes in seasonal or annual mean values. More complex methods must be used for studies that require information on how climate change may affect the frequency or timing of extreme events.

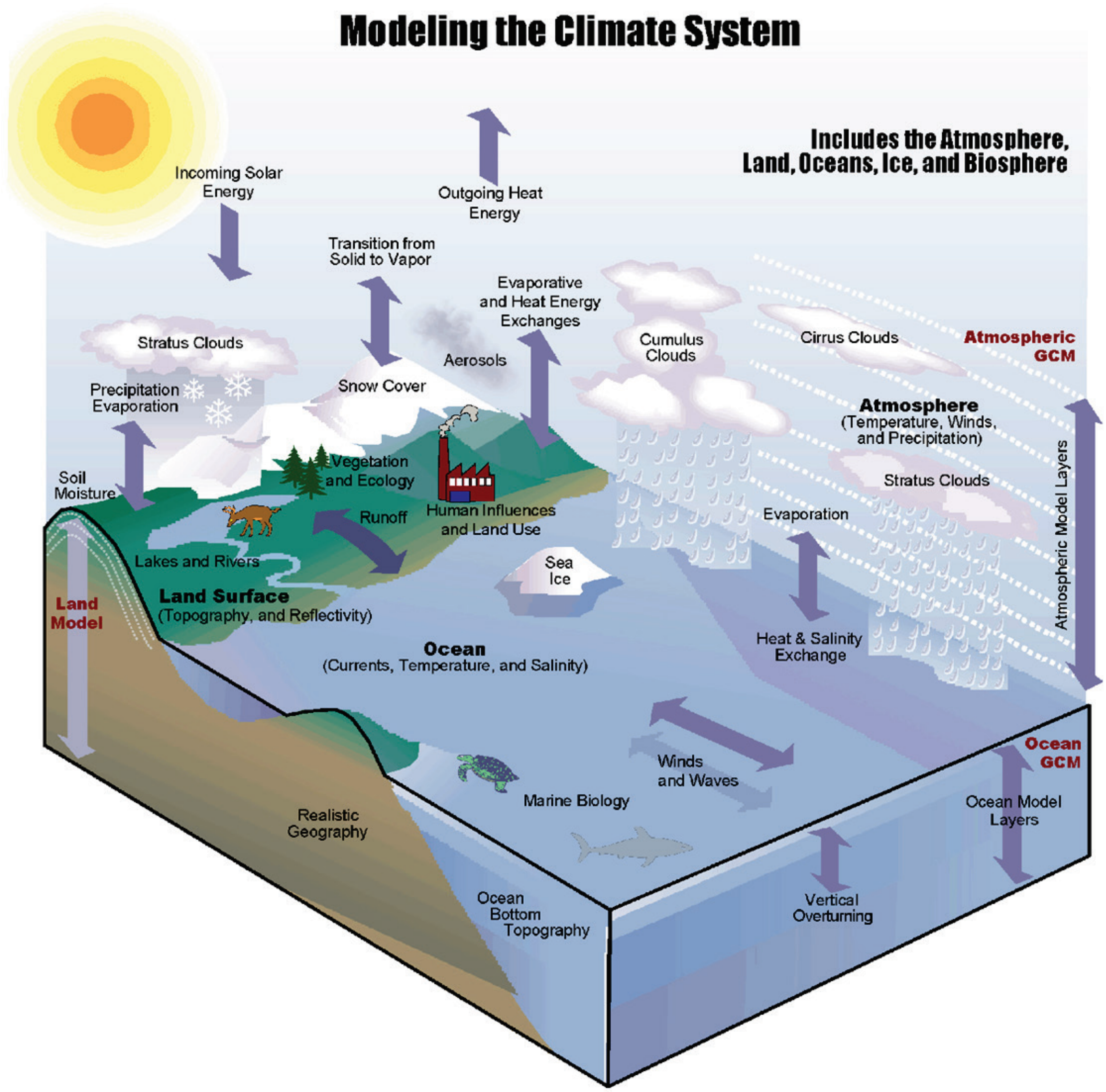

Figure 21: Modeling the Climate System

Caption: Some of the many processes that are often included in models of the Earth's climate system. (Figure source: UCAR)

Increasing Model Resolution

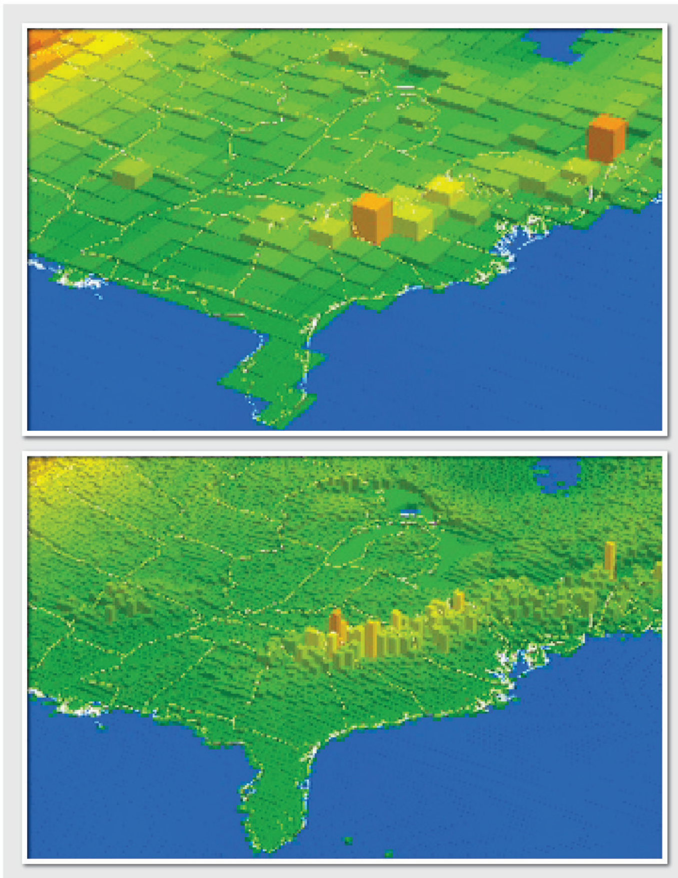

Figure 22: Increasing Model Resolution

Caption: Top) Illustration of the Eastern North American topography in a resolution of 110 km x 110 km. Bottom) Illustration of the Eastern North American topography in a resolution of 30 km x 30 km. Source:

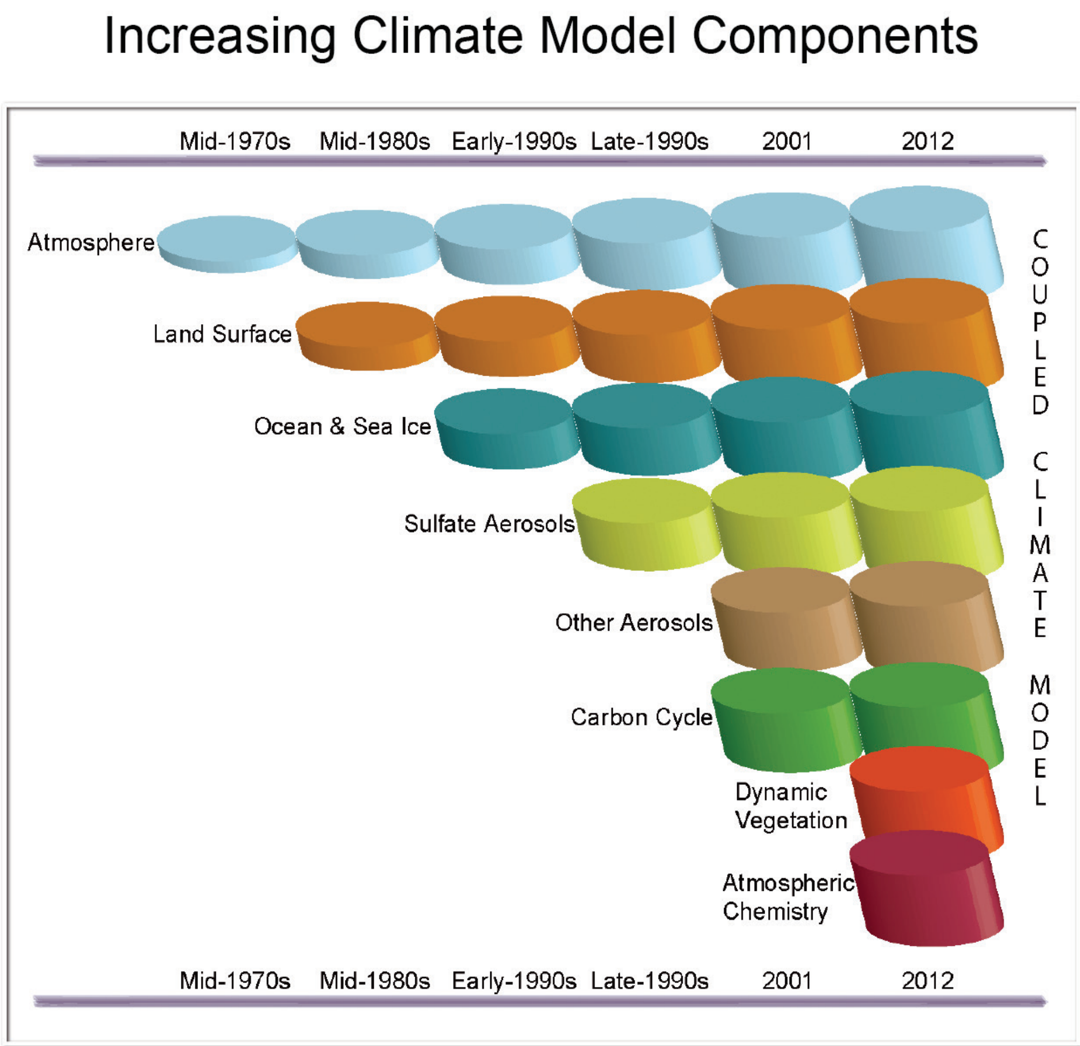

Figure 23: Increasing Climate Model Components

Caption: The development of climate models over the last 35 years showing how the different components are coupled into comprehensive climate models. Note that in the same time frame, the horizontal and vertical resolution has increased considerably and that ensembles with at least three independent experiments can now be considered as standard. (Source: IPCC)

Key Message 7.

Scientific understanding of observed temperature changes in the U.S. has greatly improved, confirming that the U.S. is warming as expected in response to global climate change. This warming is expected to continue.

Since the previous National Climate Assessment, there have been substantial advances in our understanding of the continental U.S. temperature records. Numerous studies have looked at many different aspects of the record (Fall et al. 2011; Hausfather et al. 2012 (submitted); Menne and Williams Jr 2009; Menne et al. 2009; Vose et al. 2012; Williams et al. 2012). These studies have increased confidence that the United States is warming, and refined estimates of how much.

Historical temperature data are available for thousands of weather stations. However, for a variety of practical and often unavoidable reasons, there have been frequent changes to individual stations and to the network as a whole. Two changes are particularly important. The first is a widespread change in the time at which observers read their thermometers. Second, most stations now use electronic instruments rather than traditional glass thermometers.

Extensive work has been done to document the effect of these changes on historical temperatures. For example, the change from afternoon to morning observations resulted in systematically lower temperatures for both maximum and minimum, artificially cooling the U.S. temperature record by about 0.5°F (Karl et al. 1986; Williams et al. 2012). The change in instrumentation was equally important but more complex. New electronic instruments generally recorded higher minimum temperatures, yielding an artificial warming of about 0.25°F, and lower maximum temperatures, resulting in an artificial cooling of about 0.5°F. This has been confirmed by extended period side-by-side instrument comparisons (Quayle et al. 1991). Confounding this, as noted by a recent citizen science-effort, Surfacestations.org, the new instruments were often placed nearer buildings or other man-made structures. Analyses of the changes in siting indicate that this had a much smaller effect than the change in instrumentation across the network as a whole (Fall et al. 2011; Menne et al. 2009; Williams et al. 2012).

Extensive work has been done to develop statistical adjustments that carefully remove these and other non-climate elements that affect the data. To confirm the efficacy of the adjustments, several sensitivity assessments have been undertaken. These include:

- A comparison with the U.S. Climate Reference Network (Diamond et al. submitted; Menne et al. 2009);
- Analyses to evaluate biases and uncertainties (Williams et al. 2012);
- Comparisons to a range of state-of-the-art meteorological data analyses (Vose et al. 2012); and
- In-depth analyses of the potential impacts of urbanization (Hausfather et al. 2012 (submitted))

These assessments indicate that the corrected data do not overestimate the rate of warming.

Because the average effect of these issues was to reduce recorded temperatures, adjusting for these issues tends to increase long-term warming trends. The impact is much larger for maximum temperature because the adjustments account for two distinct artificial cooling signals (that is, the change in observation time and instrumentation). The impact is smaller for minimum temperature because the artificial signals roughly offset one another (the change in observation time cooling the record, the change in instrumentation warming the record). Even without these adjustments, however, both maximum and minimum temperature records show increases over the past century.

Geographically, maximum temperature has increased in most areas except in parts of the western Midwest, northeast Great Plains, and the Southeast regions. Minimum temperature exhibits the same pattern of change with a slightly greater area of increases. The causes of these slight differences between maximum and minimum temperature are a subject of ongoing research (McNider et al. 2012). In general, the uncorrected data exhibit more extreme trends as well as larger spatial variability; in other words, the adjustments have a smoothing effect.

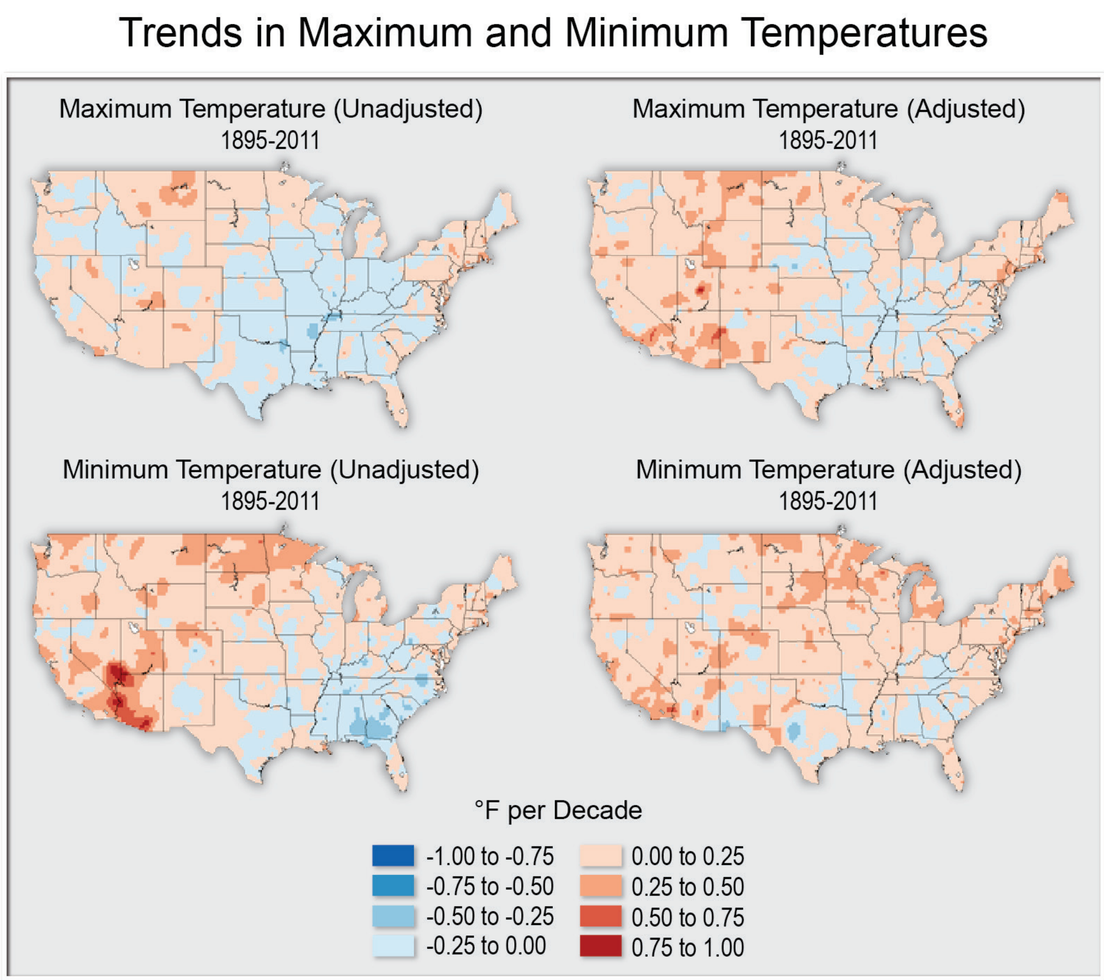

Figure 24: Trends in Maximum and Minimum Temperatures

Caption: Geographic distribution of linear trends in the U.S. Historical Climatology Network for the period 1895-2011. (Source: Updated from Menne et al. 2009)

Temperature is increasing in all four seasons. The heat that occurred during the Dust Bowl era is prominent in the summer record. The warmest summer on record was 1936, closely followed by 2011. However, twelve of the last fourteen summers have been above average. Temperatures during the other seasons have also generally been above average in recent years.

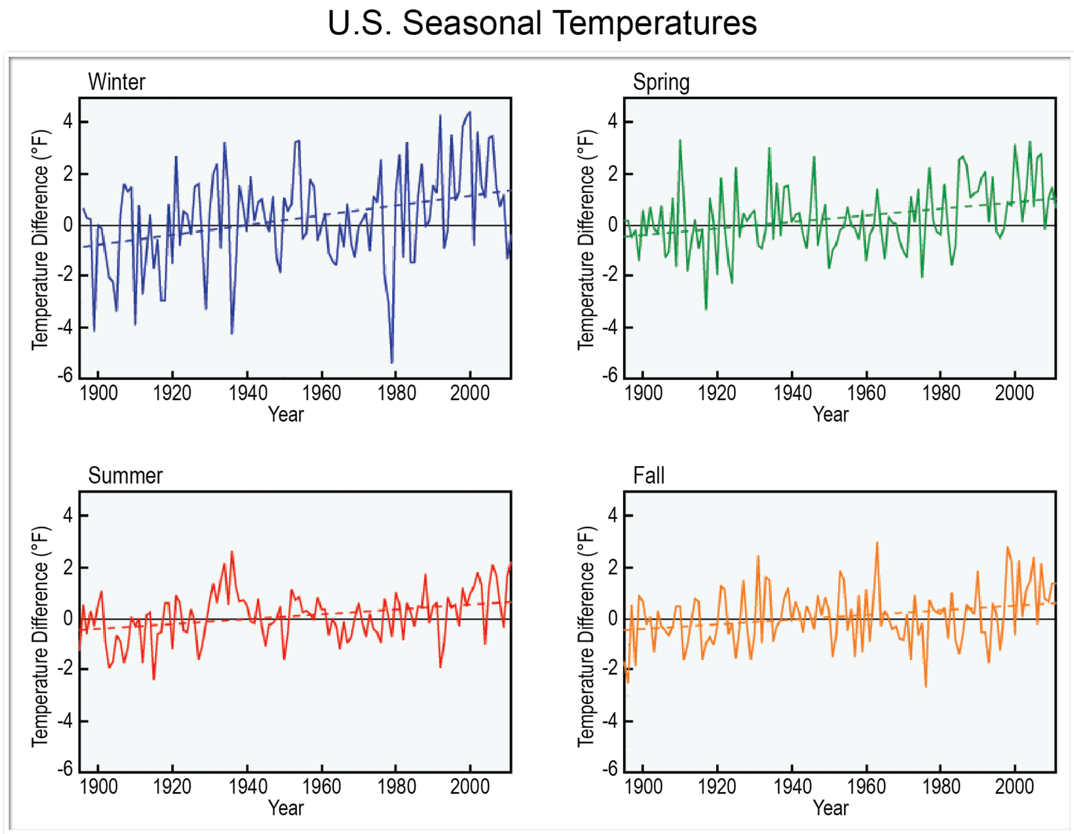

Figure 25: U.S. Seasonal Temperatures

Caption: Continental U.S. seasonal temperatures (relative to the 1901-1960 average, in °F) for winter (blue), spring (green), summer (red), and fall (orange) all show evidence of increasing trends. Dashed lines show the linear trends. Stronger trends are seen in winter and spring as compared to summer and fall. (Figure source:Kunkel et al. 2012c)

Key Message 8.

Many other indicators of rising temperatures have been observed in the U.S. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.

While surface air temperature is the most widely cited measure of climate change, other aspects of climate that are affected by temperature are often more directly relevant to both human society and the natural environment. Examples include shorter duration of ice on lakes and rivers, reduced glacier extent, earlier melting of snowpack, reduced lake levels due to increased evaporation, lengthening of the growing season, and changes in plant hardiness zones. Changes in these and many other variables are consistent with the recent warming over much of the United States. Taken as a whole, these changes provide compelling evidence that increasing temperatures are affecting both ecosystems and human society.

Striking decreases in the coverage of ice on the Great Lakes have occurred (see Key Message 10 in Chapter 2). The annual average ice cover area for the Great Lakes has shown large year-to-year variability but has sharply declined over the last 30+ years (Wang et al. 2010). Based on records covering the winters of 1972-1973 through 2010-2011, 12 of the 19 winters prior to 1991-1992 had annual average ice cover greater than 20% of the total lake area while 15 of the 20 winters since 1991-1992 have had less than 20% of the total lake area covered with ice, including the 3 lowest ice extent winters of 1997-1998, 2001-2002, and 2005-2006. A reduction in ice leading to more open waters in winter raises concerns about possible increases in lake effect snowfall. However, future trends will depend on the air-water temperature differential.

Smaller lakes in other parts of the country show similar changes, which affect recreational and commercial activities of the surrounding communities. For example, the total duration of ice cover on Lake Mendota in Madison, WI has decreased from about 120 days in the late 1800s to less than 100 days in most years since 1990 (Magnuson 2010). Average dates of spring ice disappearance on Minnesota lakes show a trend toward earlier melting over the past 60 years or so.

While shorter durations of lake ice enhance navigational opportunities during winter, decreasing water levels in the Great Lakes present risks to navigation, especially during the summer. Water levels on Lakes Superior, Michigan, and Ontario have been below their long-term (1918-2008) averages for much of the past decade (NOAA 2012). The summer drought of 2012 left Lakes Michigan and Ontario approximately one foot below their long-term averages. As noted in the previous National Climate Assessment (Karl et al. 2009), projected water level reductions in the Great Lakes range from less than a foot under lower-emission scenarios to between 1 and 2 feet under higher emission scenarios, with the smallest changes projected for Lake Superior and the largest change projected for Lakes Michigan and Huron (Hayhoe et al. 2010). However, more recent studies have indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses (Lofgren et al. 2011). Moreover, accounting for land-atmosphere feedbacks further reduces the estimates of lake level declines (MacKay and Seglenieks 2012). The most recent estimates incorporating such feedbacks indicate water level decreases for the 2021-2050 period of approximately 1 inch for Lake Superior, 2 inches for Lake Michigan/Huron and 2.4 inches for Lake Erie (MacKay and Seglenieks 2012). However, the same study indicates increasing seasonal ranges of 2.7 inches for Lake Superior and 1.6 inches for Lakes Michigan/Huron and Erie. Projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty.

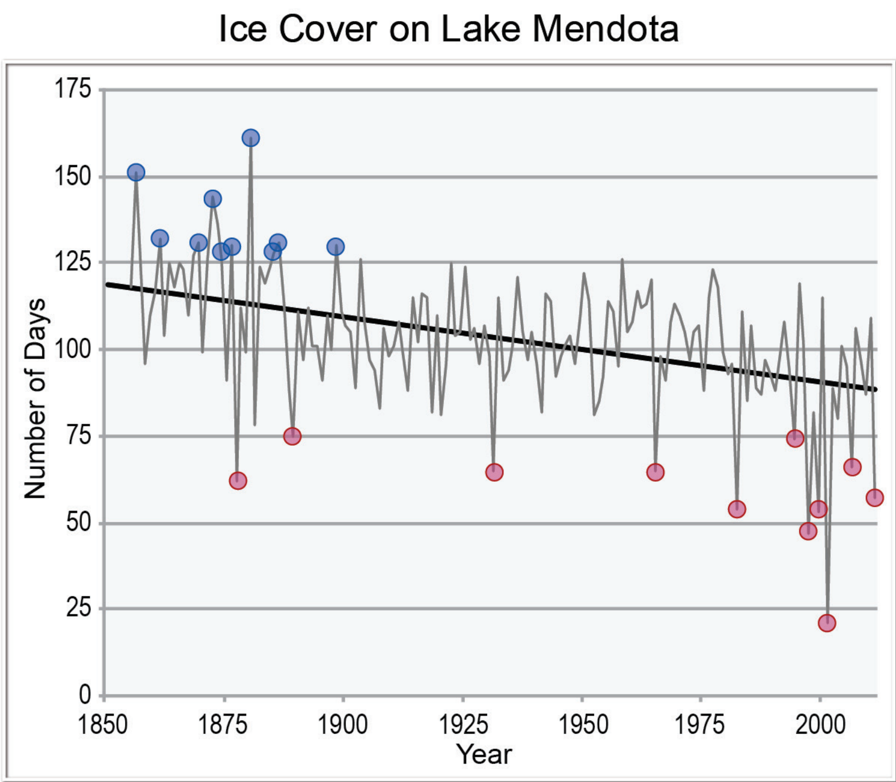

Figure 26: Ice Cover on Lake Mendota

Caption: The duration, or number of days, of ice cover on Lake Mendota, Wisconsin has decreased over time. The 10 longest and 11 shortest ice seasons are marked by blue and red circles, respectively. Seven of the 10 shortest ice cover seasons have occurred since 1980. Data from the Wisconsin State Climatology Office: Madison Lakes Ice Summary.

A long-term record of the ice-in date (the first date in winter when ice coverage closes the lake to navigation) on Lake Champlain in Vermont (http://www.erh.noaa.gov/btv/climo/lakeclose.shtml) shows that the lake now freezes approximately two weeks later than in the early 1800s and over a week later than 100 years ago. Later ice-in dates are an indication of higher lake temperatures, as it takes longer for the warmer water to freeze in winter. Prior to 1950, the absence of winter ice cover on Lake Champlain was rare, occurring three times in the 1800s and another four times between 1900 and 1950. It remained ice-free during 42% of the winters between 1951 and 1990. Since 1991, Lake Champlain has remained ice-free during 64% of the winters. One- to two-week advances of ice breakup dates and similar delays of freeze-up dates are also typical of lakes and rivers in Canada, Scandinavia, and northern Asia (IPCC 2007).

In the U.S. Southwest, there have been many indications of a changing climate over the last five decades: mountain snowpack decreased (as it did over western North America as a whole) (Mote et al. 2005), the dates of snowmelt runoff in California and across the West shifted to earlier in the year (Dettinger and Cayan 1995; Stewart et al. 2005), spring in the U. S. West began earlier (as indicated by shifts in the timing of plant blooms and spring snowmelt-runoff pulses) (Cayan et al. 2001), general shifts in western hydroclimatic seasons (Regonda et al. 2005), and trends toward more precipitation falling as rain instead of snow over the West (Knowles et al. 2006). The ratio of precipitation falling as rain rather than snow, the amount of water in snowpack, and the timing of peak stream flow on snowmelt-fed rivers all changed as expected with warming over the past dozen years, relative to the last century baselines (Barnett et al. 2008).

Streamflow from Snowmelt Shifts to Earlier in Year

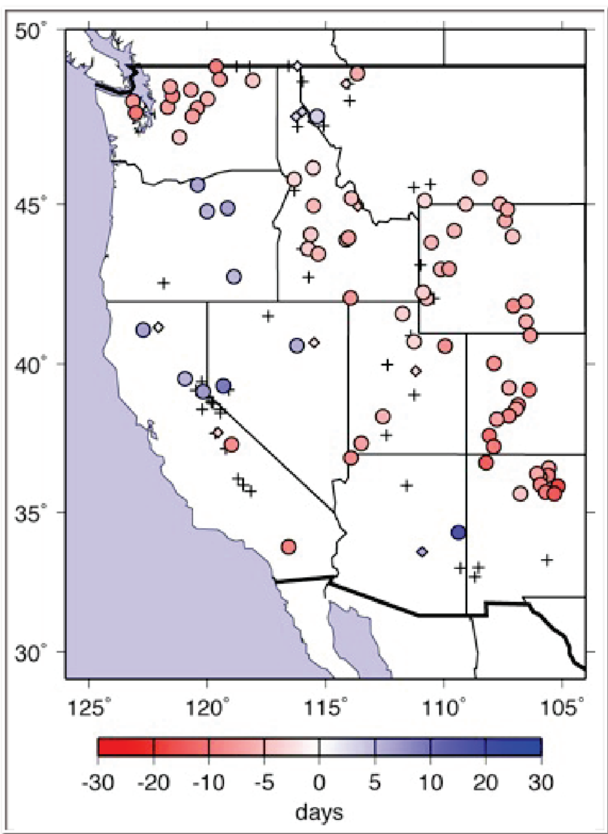

Figure 27: Streamflow from Snowmelt Shifts to Earlier in Year

Caption: At many locations in the western U.S., the timing of streamflow in rivers fed by snowpack is shifting to earlier in the year. Stream gauge locations where half of the annual flow is now arriving anywhere from 5 to 20 days earlier each year for 2001-2010, relative to the 1951-2000 average, are indicated by red dots; locations where the annual flow is now arriving later are indicated by blue dots. Crosses indicate locations where observed changes are not statistically different from the past century baseline at 90% confidence levels, diamonds indicate gauges where the timing difference was significantly different at 90% confidence and dots indicate gauges where timing was different at 95% confidence level. (Updated from Stewart et al. 2005).

Changing temperatures affect vegetation through the frost-free season length, the growing season length, and plant tolerance thresholds. U.S. average frost-free season length (defined as the number of days between the last and first occurrences of 32°F in spring and autumn, respectively) increased by about two weeks during the last century (Kunkel et al. 2004). The increase was much greater in the western than in the eastern United States. Consistent with the recent observed trends in frost-free season length, the largest projected changes in growing season length are in the mountainous regions of the West, while smaller changes are projected for the Midwest, Northeast, and Southeast. Related plant and animal changes include a northward shift in the typical locations of bird species (National Audubon Society 2009) and a shift since the 1980s toward earlier first leaf dates for lilac and honeysuckle (EPA 2010)

Plant hardiness zones are determined primarily by the extremes of winter cold (Daly et al. 2010). While maps of plant hardiness have guided the selection of plants for both ornamental and agricultural purposes, these zones are subject to change as climate changes. Plant hardiness zones for the U.S. have recently been updated using the new climate normals (1981-2000), and these zones show a northward shift by up to 100 miles relative to the zones based on the older (1971-2000) normals. Even greater northward shifts, as much as 200 miles, are projected over the next 30 years as warming increases. Projected shifts are largest in the major agricultural regions of the central U.S.

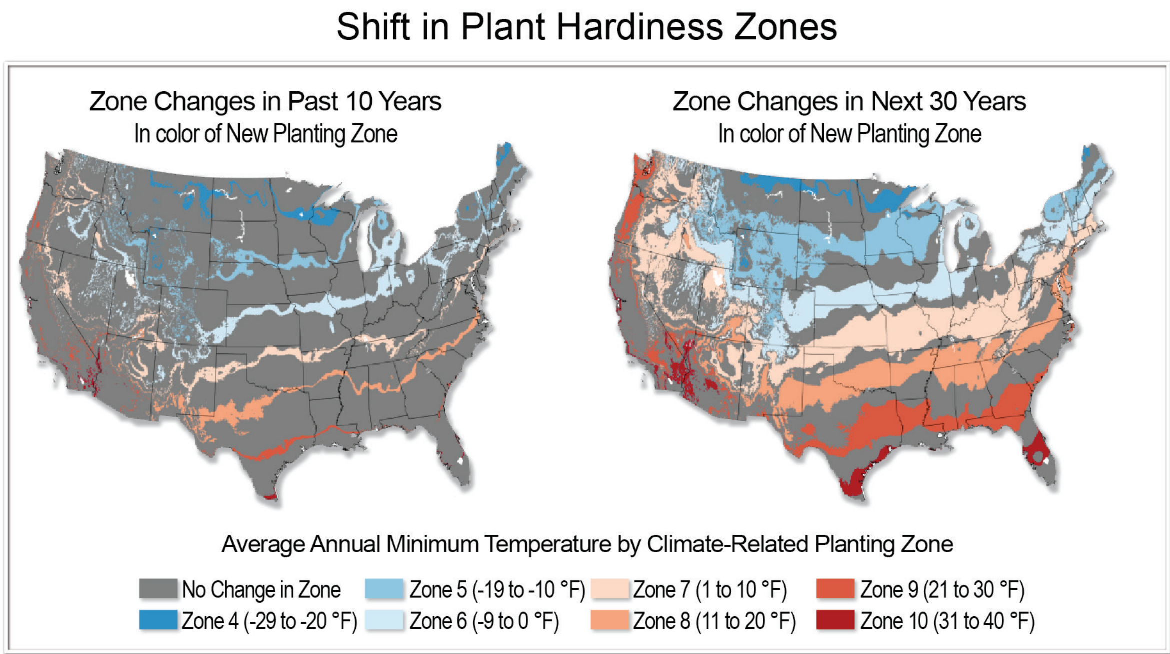

Figure 28: Shifts in Plant Hardiness Zones

Caption: The map on the left above shows the change in Plant Hardiness Zones calculated from those based on the 1971-2000 climate to those based on the 1981-2010 climate. Even greater changes are projected over the next 30 years (map on right). (Figure source: NOAA)

Key Message 9.

There have been observed trends in some types of extreme weather events, and these are consistent with rising temperatures. These include increases in: heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate changes' effects on other types of extreme events continues.

High impact, large-scale extreme events are complex phenomena involving various factors that can often create a "perfect storm." Such extreme weather occurs naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events.

Observations show that heavy downpours have already increased across the U.S. Regional and global models project continued widespread increases in extreme precipitation over the continental U.S. and Alaska, consistent with these observed changes ((Wehner 2012). Precipitation events tend to be limited by available moisture. For the very rarest events, there is strong evidence from observations (Kunkel et al. 2012a) and models (Gutowski et al. 2008); (Li et al. 2011); (Wehner 2012) that higher temperatures and the resulting moister atmosphere are the main cause of these observed and projected increases. Other factors that may also have an influence on observed U.S. changes in extreme precipitation are land-use changes (for example, changes in irrigation, DeAngelis et al. 2010; Groisman et al. 2012) and a shift in the number of El Niño events versus La Niña events.

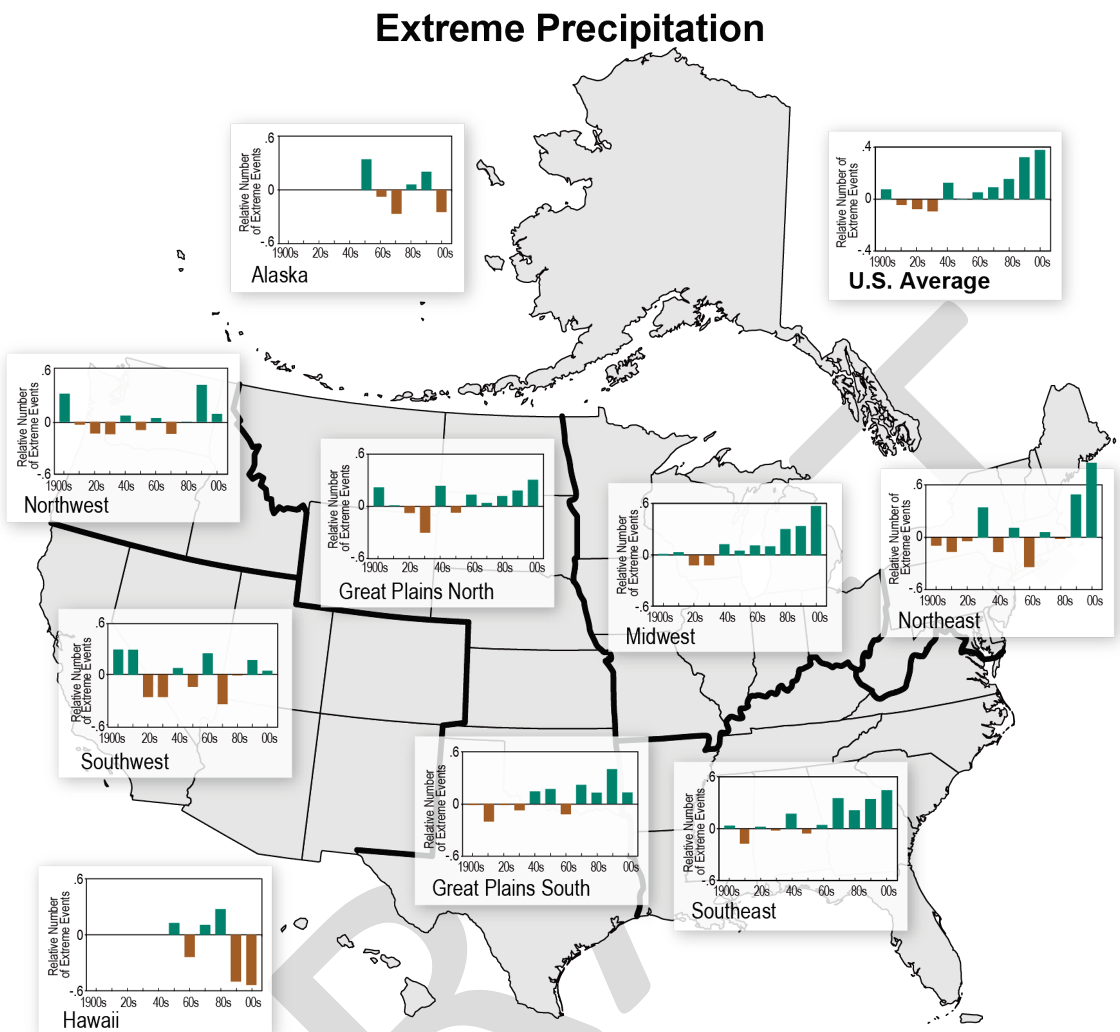

Figure 29: Extreme Precipitation

Caption: Heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast (Kunkel et al. 2012a). Despite considerable decadal-scale natural variability, indices such as this one based on 2-day precipitation totals exceeding a threshold for a 1-in-5-year occurrence exhibit a greater than normal occurrence of extreme events since 1991 in all U.S. regions except Alaska and Hawaii. Each bar represents that decade's average, while the far right bar in each graph represents the average for the 11-year period of 2001-2011. Analysis based on 930 long-term, quality-controlled station records. (Figure source: NOAA NCDC / CICS-NC. Data from NOAA NCDC.)

Climate change can also alter the characteristics of the atmosphere in ways that affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an increasing trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms (also referred to as extra-tropical [outside the tropics] cyclones (Kunkel et al. 2012b)).

There is also a northward shift in storms (Vose et al. 2012; Wang et al. 2009) which are often associated with extreme precipitation over the U.S. This shift is consistent with projections of a warming world (Bengtsson et al. 2009; Neu 2009). No change in mid-latitude storm intensity or frequency has been detected.

In the tropics, the most important types of storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer category 1 and 2 hurricanes and more category 4 and 5 hurricanes. There has been no significant trend in the global number of tropical cyclones (IPCC 2011) nor has any trend been identified in the number of U.S. landfalling hurricanes (Karl et al. 2009). Projections of future storm frequency suggest global numbers may slightly decrease (IPCC 2011). Two studies have found an upward trend in the number of extreme precipitation events associated with tropical cyclones (Knight and Davis 2009; Kunkel et al. 2010), but significant uncertainties remain (Groisman et al. 2012). A change in the number of Atlantic hurricanes has been identified, but interpreting its significance is complicated both by multi-decadal natural variability and the reliability of the pre-satellite historical record (Holland and Webster 2007; Landsea 2007; Mann et al. 2007b). The global satellite record shows a shift toward stronger tropical cyclones (IPCC 2011; Kossin et al. 2007), Elsner et al. (2008) but does not provide definitive evidence of a long-term trend. Nonetheless, there is a growing consensus based on our scientific understanding and very high resolution atmospheric modeling, that the strongest tropical cyclones, including Atlantic hurricanes, will become stronger in a warmer world (Emanuel 2000; Knutson et al. 2010).

The number of heat waves has been increasing in recent years. On a decadal basis, the decade of 2001-2010 had the second highest number since 1901 (first is the 1930s). This trend has continued in 2011 and 2012, with the number of intense heat waves being almost triple the long-term average. Regionally, the Northwest, Southwest, and Alaska had their highest number of heat waves in the 2000s, while the 1930s were the highest in the other regions (note that the Alaskan time series begins in the 1950s). For the number of intense cold waves, the national-average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent throughout the contiguous U.S. and Alaska. Climate model simulations indicate that the recent trends toward increasing frequency of heat waves and decreasing frequency of cold waves will continue in the future.

The data on the number and intensity of severe thunderstorm phenomena (including tornadoes, thunderstorm winds, and hail) are not of sufficient quality to determine whether there have been historical trends (Kunkel et al. 2012a). Furthermore, since the phenomena are too small to be directly represented in climate models, future changes remain uncertain. (Peterson et al. 2012)

Key Message 10.

Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire U.S.

Temperature increases also increase evaporation rates (Peterson et al. 2012). The Palmer Drought Severity Index (PDSI) (Alley 1984; Palmer and Bureau 1965), a widely used indicator of dryness that incorporates both precipitation and temperature-based evaporation estimates, does not show any trend for the U.S. as a whole over the past century (Dai et al. 2004). However, drought intensity and frequency have been increasing over much of the West, especially during the last four decades. In the Southeast, western Great Lakes, and southern Great Plains droughts have increased during the last 40 years but do not show an increase when examined over longer periods encompassing the entire last century. In the Southwest, drought has been widespread since 2000. In fact, the average value of the PDSI during the 2000s indicated the most severe average drought conditions of any decade. The severity of recent drought in the Southwest reflects both the decade's low precipitation and high temperatures.

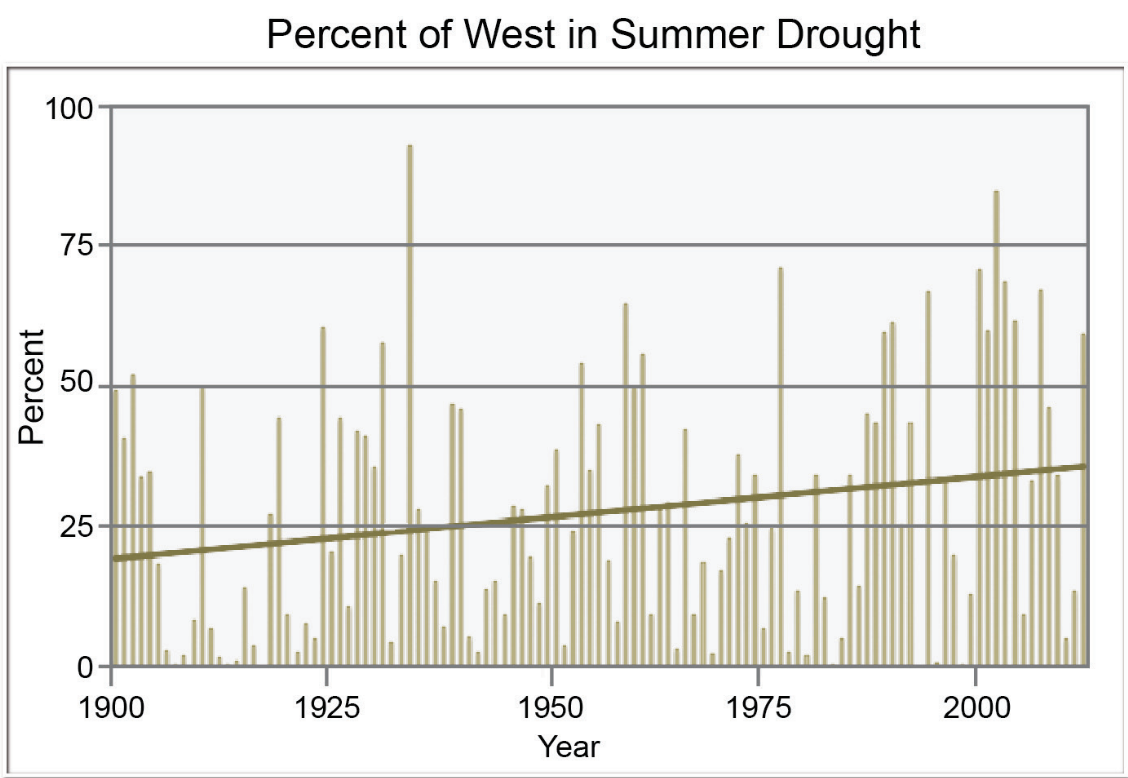

Figure 30: Percent of West in Summer Drought

Caption: The area of the western U.S. in moderately to extremely dry conditions during summer (June-July-August) varies greatly from year to year but shows a long-term increasing trend from 1900 to 2012. Data from NOAA NCDC State of the Climate Drought analysis.

Seasonal and multi-year droughts affect wildfire severity (Brown et al. 2008; Littell et al. 2009; Schoennagel 2011; Westerling et al. 2003). For example, persistent drought conditions in the Southwest, combined with wildfire suppression and land management practices (Allen et al. 2002), have contributed to wildfires of unprecedented size since 2000. Five western states (Arizona, Colorado, Utah, California, and New Mexico) have experienced their largest fires on record at least once since 2000. Much of the increase in fires larger than 500 acres occurred in the western United States, while the area burned in the Southwest increased more than 300% relative to the area burned during the 1970s and early 1980s (Westerling et al. 2006).

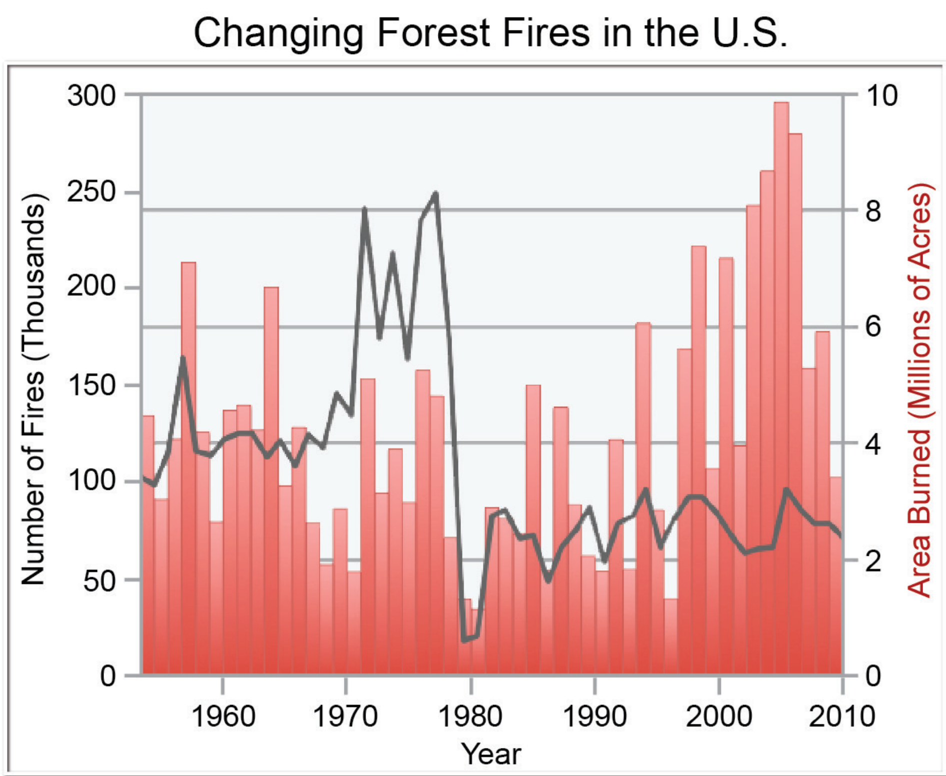

Figure 31: Changing Forest Fires in the U.S.

Caption: Although the average number of wildfires per year (black line) has decreased over time, the total area burned by wildfires (red bars) in the continental U.S. (primarily in the Western states) has nearly doubled since 2000 relative to the long-term 1960-1999 average. Data from the National Interagency Fire Center, for 1960 to 2011.

Future changes in droughts on a duration and scale that affect agriculture are projected to increase in frequency and severity in this century due to higher temperatures. Projections of the Palmer Drought Severity Index at the end of this century indicate that the normal state for most of the nation would be considered moderate to severe drought today (Wehner et al. 2011) . Despite its widespread usage, this index may be overly sensitive to future temperature increases. However, a direct examination of future soil moisture content projections also shows drying in most areas of the western U.S.

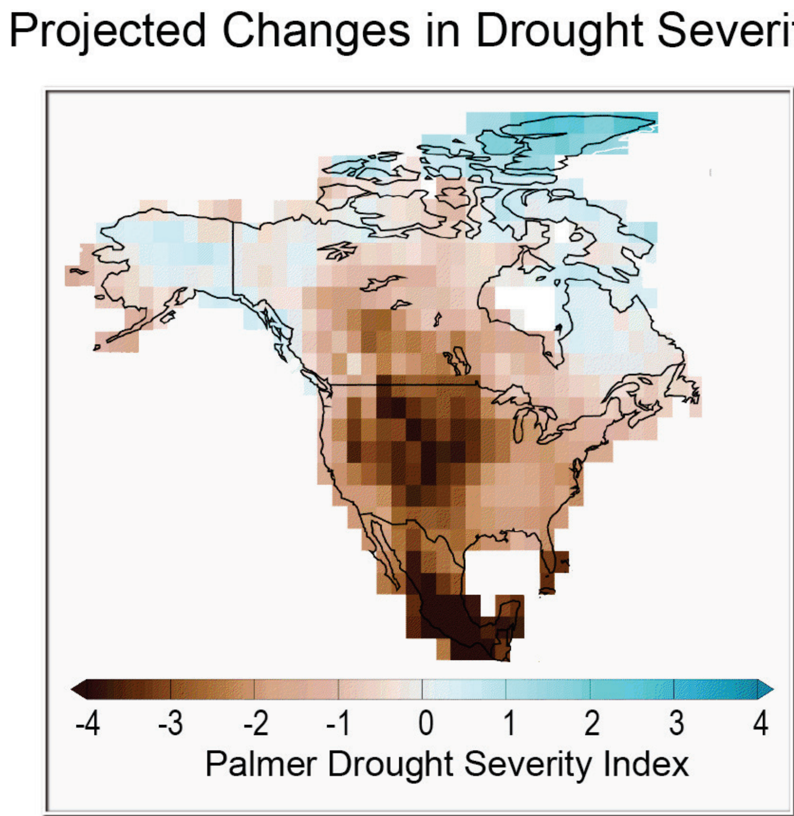

Figure 32: Projected Changes in Drought Severity

Caption: Projected Palmer Drought Severity Index at the end of this century from the CMIP3 models under the emissions scenario SRESA1B. Values less than –2 are termed by NOAA as "moderate drought," less than –3 as "severe drought," and less than –4 as "extreme drought". (Wehner et al. 2011).

Provided fuels are available, the area of forest burned in many mid-latitude areas, including the western U.S., may increase substantially as temperature and evapotranspiration increase, exacerbating drought (Moritz et al. 2012). Under even relatively modest amounts of warming, significant increases in area burned are projected in the Sierra Nevada, southern Cascades, and coastal California; in the mountains of Arizona and New Mexico; on the Colorado Plateau; and in the Rocky Mountains (Spracklen et al. 2009). Other studies, examining a broad range of climate change and development scenarios, find increases in the chance of large fires for much of northern California's forests (Westerling and Bryant 2008)).

Consecutive days with little or no precipitation can also reduce soil moisture. The average annual maximum number of consecutive dry days are projected to increase for the higher emissions scenarios in areas that are already prone to little precipitation by mid-century. Specifically, most of the western and southwestern U.S. is projected to experience statistically significant increases in the annual maximum number of consecutive dry days, up to 26 days above present-day values for parts of southern California and Arizona. The only sizeable area with statistically significant decreases in consecutive dry days is the north-central U.S.

Key Message 11.

Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land and sea-based ice is expected to continue with further warming.

A changing climate is affecting the Arctic on land and sea. Increasing temperatures and associated impacts are apparent throughout the Arctic, especially Alaska. Sea ice coverage and thickness, permafrost on land, mountain glaciers, and the Greenland Ice Sheet all show changes consistent with higher temperatures.

The most dramatic decreases in summer sea ice have occurred along the northern coastline of Alaska and Russia. Since the satellite record began in 1979, September (summer minimum) sea ice extent has declined by 13% per decade in the Beaufort Sea and 32% per decade in the Chukchi Sea (Meier et al. 2012), leaving the Chukchi nearly ice-free in the past few Septembers. Longer-term records based on climate proxies suggest that pan-Arctic ice extent in summer is the lowest it has been in at least the past 1,450 years (Kinnard et al. 2011). The fact that winter ice extent has declined less than summer ice extent (see Ch. 3: Our Changing Climate, Key Message 10) is indicative of a trend toward only seasonal ice cover, which is relatively thin and vulnerable to melt in the summer. Recent work has indicated that the loss of summer sea ice may be affecting the atmospheric circulation in autumn and early winter. For example, there are indications that a weakening of sub-polar westerly winds during autumn is an atmospheric response to a warming of the lower troposphere of the Arctic (Overland and Wang 2009). Extreme summer ice retreat also appears to be increasing the persistence of associated mid-latitude weather patterns, which may lead to an increased probability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves (Francis and Vavrus 2012). However, the combination of interannual variability and the small sample of years with extreme ice retreat make it difficult to identify a geographically consistent atmospheric response pattern in the middle latitudes.

Arctic Sea Ice Decline

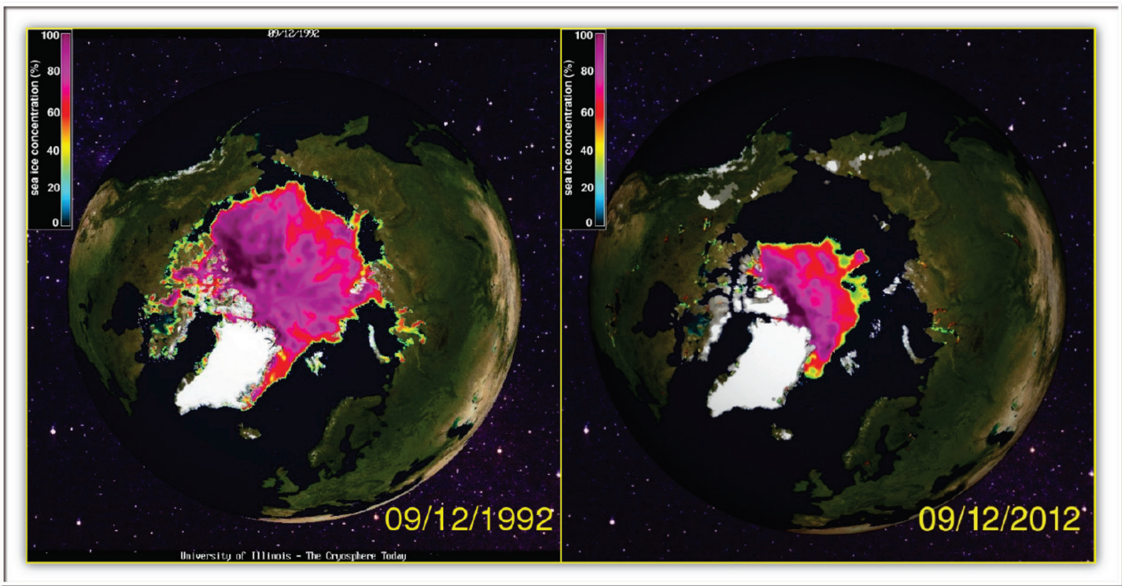

Figure 33: Arctic Sea Ice Decline

Caption: The spatial extent of Arctic sea ice cover in September has decreased substantially in the past two decades. The reduction of September extent from 1992 (left) to 2012 (right) has been nearly 50%. (Figure source: University of Illinois, The Cryosphere Today)

On land, changes in permafrost provide compelling indicators of climate change as they tend to reflect long-term average changes in climate. Borehole measurements are particularly useful as they provide information from levels below about 10-meter depth where the seasonal cycle becomes negligible. Increases in borehole temperatures over the past several decades are apparent at various locations, including Alaska, northern Canada, Greenland, and northern Russia. The increases are about 3.6°F at the two stations in northern Alaska (Deadhorse and West Dock). In northern Alaska and northern Siberia where permafrost is cold and deep, thaw of the entire permafrost layer is not imminent. However, in the large areas of discontinuous permafrost of Russia, Alaska, and Canada, average annual temperatures are sufficiently close to freezing that permafrost thaw is a risk within this century. Thawing of permafrost can release methane into the atmosphere, amplifying warming, as well as potentially causing infrastructure and environmental damages.

Permafrost Temperatures Rising

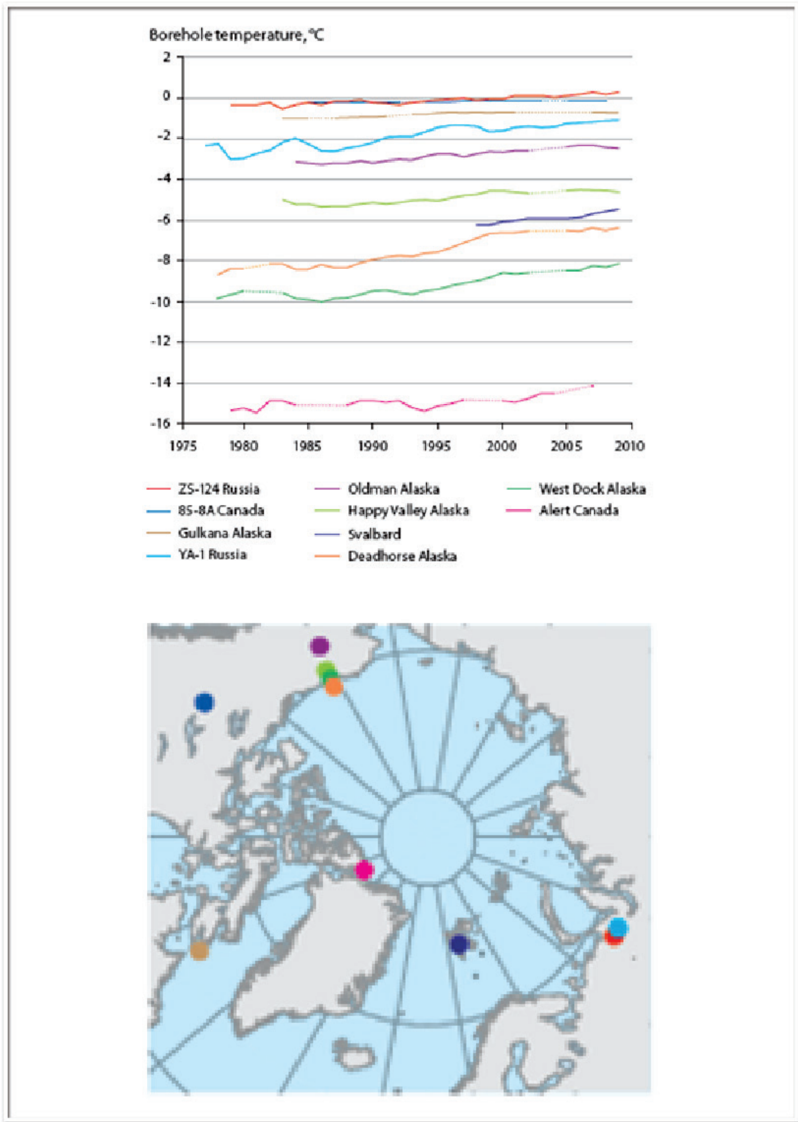

Figure 34: Permafrost Temperatures Rising

Caption: Ground temperatures at depths between 10 and 20 meters for boreholes across the circumpolar northern permafrost regions (Callaghan and Johansson 2012; Romanovsky et al. 2010).

There is evidence that the active layer (the near-surface layer of seasonal thaw, typically up to three feet deep) may be thickening in many areas of permafrost, including in northern Russia and Canada (Callaghan and Johansson 2012). Permafrost thaw in coastal areas increases the vulnerability of coastlines to erosion by ocean waves, which in turn are exacerbated by the loss of sea ice from coastal areas affected by storms.

Glaciers are retreating over much of the Northern Hemisphere. Over the past decade, the contribution to sea level rise from glaciers and small ice caps (excluding Greenland) has been comparable to the contributions from the Greenland Ice Sheet (Cogley 2009; Romanovsky et al. 2010).

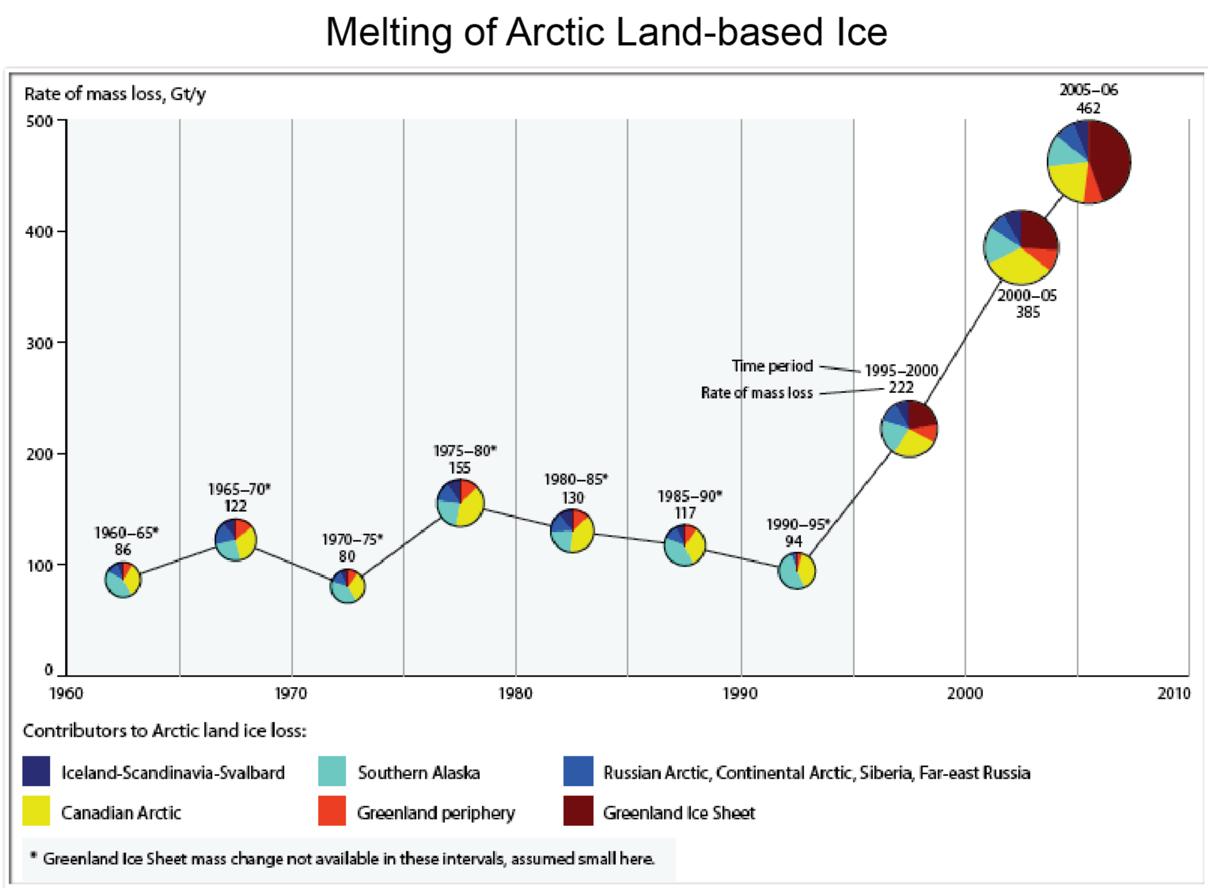

Figure 35: Melting of Arctic Land-based Ice

Caption: Inputs of freshwater to the ocean from mountain glaciers, small ice caps, and the Greenland Ice Sheet have increased dramatically in the past two decades. The size of the circles in the figure is proportional to the five-year average freshwater contributions to the ocean from melting of land-based ice. The coloring indicates the relative contributions from the Greenland Ice Sheet (brown) and mountain glaciers from the Greenland periphery (orange), Iceland-Scandinavia-Svalbard (dark blue), the Canadian Arctic (yellow), southern Alaska (light blue), and the Russian Arctic (medium blue). The largest contributions from mountain glaciers have been from the Canadian Arctic and southern Alaska. Note that contributions from mass changes of the Greenland Ice Sheet are not available prior to the mid-1990s, but they are assumed to have been small during this earlier period because annual snow accumulation was in approximate balance with annual meltwater discharge. Figure from (Cogley 2009).

Projections of future mass loss by glaciers and small ice caps indicate a continuation of current trends, although these projections are based on only the changes in temperature and precipitation projected by global climate models; they do not include the effects of dynamical changes (for example, glacier movement). While there is a wide range among the projections derived from different global climate models, the models are consistent in indicating that the effects of warming will outweigh the effects of increases in snowfall. The regions from which the contributions to sea level are projected to be largest are the Canadian Arctic, Alaska, and the Russian Arctic (Arctic Monitoring and Assessment Programme 2011).

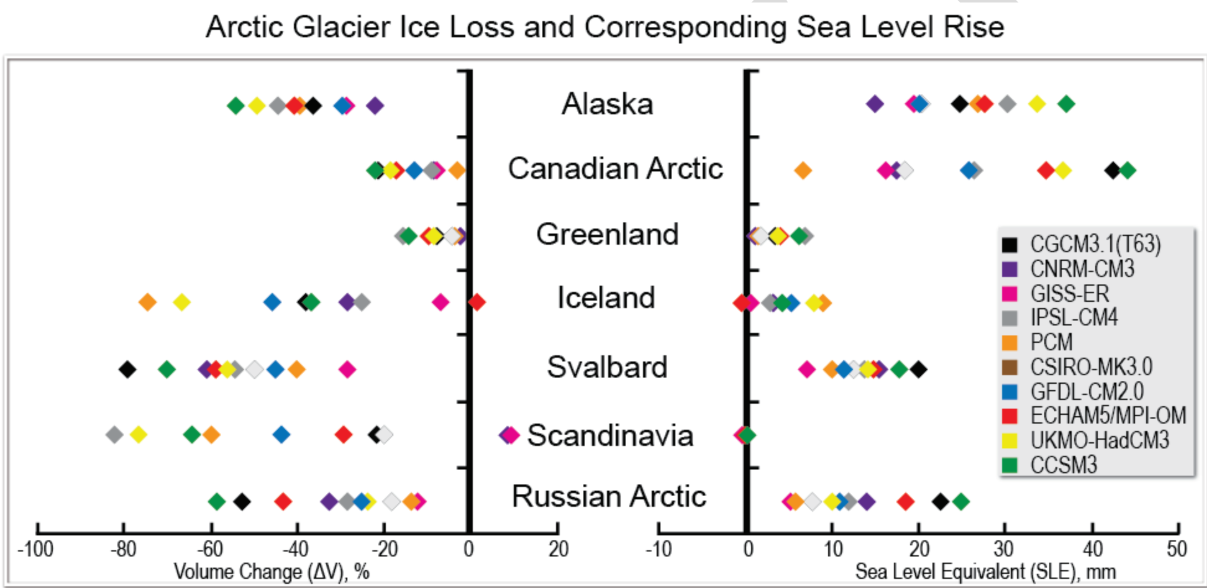

Figure 36: Arctic Glacier Ice Loss and Corresponding Sea Level Rise

Caption: Projections of fractional volume change and the equivalent sea level rise by 2100 for seven geographical regions that include all Arctic glaciers. Projections are based on temperature and precipitation simulated by ten different global climate models from CMIP3. For each region, the estimates are shown in different colors corresponding to the ten different models (inset box). Negative volume changes (-%) represent a net loss of ice (left), and corresponding contributions to sea level rise (right) (Radić and Hock 2011).

Key Message 12.

Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of temperature change and on the ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

Rising sea levels are one of the hallmarks of a warming planet. They will also be one of the major impacts of human-caused global warming on both human society and the natural environment.

Global sea level increases are primarily caused by one of two different processes. First, the oceans absorb more than 90% of the excess heat trapped by human interference with the climate system, and this winds up warming the oceans (Church et al. 2011). Like mercury in a thermometer, the warmer ocean water expands, contributing to global sea level rise. Second, the warmer climate also causes melting of glaciers and ice sheets. This meltwater eventually runs off into the ocean and contributes to sea level rise as well. A recent synthesis of surface and satellite measurements of the ice sheets shows that the rate at which the Greenland and Antarctic ice sheets contribute to sea level rise has been increasing rapidly and has averaged 0.59 +/– 0.20 millimeters per year since 1992, with Greenland's contribution being more than double that of Antarctica (Shepherd et al. 2012). In addition, local sea level change can differ from the global average sea level rise due to changes in ocean currents, local land movement, and even changes in the gravitational pull of the ice sheets and changes in the Earth's rotation.

There is high confidence that global sea level will continue to rise over this century, and that most coastlines will see higher waters. The rates of sea level rise along individual coastlines, however, remain difficult to predict as they can vary depending on the region. For example, globally averaged sea level has risen steadily by about 2.4 inches) over the past two decades. But during that time, many regions have seen much more rapid rise and some have experienced falling sea levels. These complicated patterns are caused by changes in ocean currents and movement of heat within the oceans. Many of these patterns are due in part to natural, cyclic changes in the oceans. On the west coast of the United States, sea level has fallen slightly since the early 1990s. Recent work suggests that a natural cycle known as the Pacific Decadal Oscillation has counteracted most or all of the global sea level signal there. This means that in coming decades the west coast is likely to see faster than average sea level rise as this natural cycle changes mode (Bromirski et al. 2011).

Along any given coastline, determining the rate of sea level rise is complicated by the fact that the land may be rising or sinking. Along the Gulf Coast, for example, local geological factors including extraction of oil, natural gas, and water from underground reservoirs are causing the land to sink, which could increase the effect of global sea level rise by several inches by the end of this century (Ivins et al. 2007). Predicting the future of any single coastline requires intimate knowledge of the local geology as well as the processes that cause sea levels to change at both the local and global scale.

Future projections of sea levels along U.S. coastlines also require information about distant sources of sea level rise, such as loss of ice from the great ice sheets on Greenland and

Antarctica. These continents hold enough ice to raise global sea levels by more than 200 feet if they were to melt completely. While this is unlikely over at least the next few centuries, studies suggest that meltwater from ice sheets could contribute anywhere from several inches to 4.5 feet to global sea levels by the end of this century (Willis and Church 2012). Because their behavior in a warming climate is still very difficult to predict, these two ice sheets are the biggest wildcards for potential sea level rise in the coming decades. What is certain is that these ice sheets are already responding to the warming of the oceans and the atmosphere. Satellites that measure small changes in the gravitational pull of these two regions have proven that both Greenland and Antarctica are currently losing ice and contributing to global sea level rise (Chen et al. 2009; Khan et al. 2010).

In the United States, an estimated 5 million people currently live within 4 feet of current high tide lines, which places them at increasing risk of flooding in the coming decades (Strauss et al. 2012). Although sea level rise is often thought of as causing a slow inundation, the most immediate impacts of sea level rise are to increase high tides and storm surges. A recent assessment of flood risks in the United States found that the odds of experiencing a "100-year flood" are on track to double by 2030.

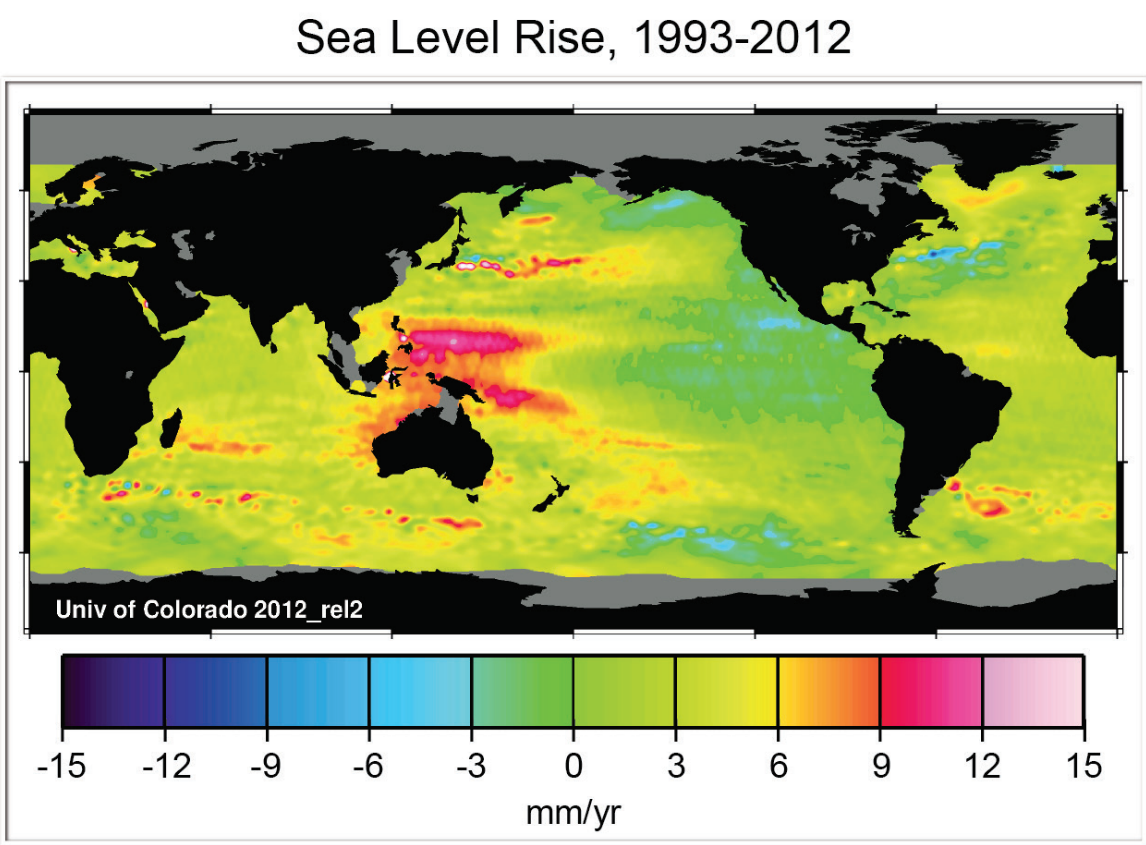

Figure 37: Sea Level Rise, 1993-2012

Caption: The patterns of sea level rise between 1993 and 2012 as measured by satellites. The complicated patterns are a reminder that sea levels do not rise uniformly (Nerem et al. 2010).

Ice Loss from Greenland and Antarctica

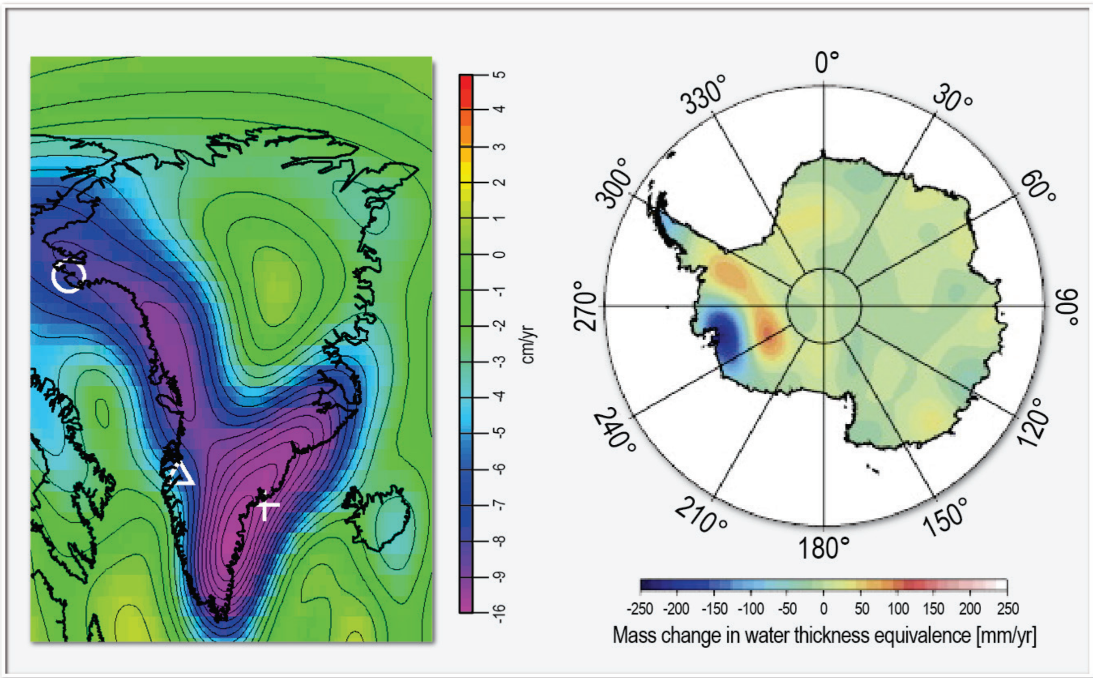

Figure 38: Ice Loss from Greenland and Antarctica

Caption: (left) rate of ice mass loss from Greenland (Khan et al. 2010). (right) rate of ice mass loss from Antarctica (Chen et al. 2009). The GRACE (Gravity Recovery and Climate Experiment) satellites measure changes in the pull of gravity over these two continents. As they lose ice to the oceans, the gravitational pull of Greenland and Antarctica is reduced. GRACE has now proven that both of the major ice sheets are currently contributing to global sea level rise due to ice loss.

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