Chapter 6

Impacts and Adaptation

In its June 2001 report, the Committee on the Science of Climate Change, which was convened by the National Research Council (NRC) of the National Academy of Sciences, concluded that "[h]uman-induced warming and associated sea level rises are expected to continue through the 21st century." The Committee recognized that there remains considerable uncertainty in current understanding of how climate varies naturally and will respond to projected, but uncertain, changes in the emissions of greenhouse gases and aerosols. It also noted that the "impacts of these changes will be critically dependent on the magnitude of the warming and the rate with which it occurs" (NRC 2001a).

SUMMARY OF THE NATIONAL ASSESSMENT

To develop an initial understanding of the potential impacts of climate change for the United States during the

21st century, the U.S. Global Change Research Program has sponsored a wide-ranging set of assessment activities since the submission of the Second National Communication in 1997. These activities examined regional, sectoral, and national components of the potential consequences for the environment and key societal activities in the event of changes in climate consistent with projections drawn from the Intergovernmental Panel on Climate Change (IPCC). Regional studies ranged from Alaska to the Southeast and from the Northeast to the Pacific Islands. Sectoral studies considered the potential influences of climate change on land cover, agriculture, forests, human health, water resources, and coastal areas and marine resources. A national overview drew together the findings to provide an integrated and comprehensive perspective.

These assessment studies recognized that definitive prediction of potential outcomes is not yet feasible as a result of the wide range of possible future levels of greenhouse gas and aerosol emissions, the range of possible climatic responses to changes in atmospheric concentration, and the range of possible environmental and societal responses. These assessments, therefore, evaluated the narrower question concerning the vulnerability of the United States to a specified range of climate warming, focusing primarily on the potential consequences of climate scenarios that project global average warming of about 2.5 to almost 4ºC (about 4.5–7ºF). While narrower than the IPCC's full 1.4–5.8ºC (2.5–10.4ºF) range of estimates of future warming, the selection of the climate scenarios that were considered recognized that it is important to treat a range of conditions about the mid-range of projected warming, which was given by the NRC as 3ºC (5.4ºF). Similarly, assumption of a mid-range value of sea level rise of about 48 cm (19 inches) was near the middle of the IPCC's range of 9–88 cm (about 4–35 inches) (2001d).

Because of these ranges and their uncertainties, and because of uncertainties in projecting potential impacts, it is important to note that this chapter cannot present absolute probabilities of what is likely to occur. Instead, it can only present judgments about the relative plausibility of outcomes in the event that the projected changes in climate that are being considered do occur. To the extent that actual emissions of greenhouse gases turn out to be lower than projected, or that climate change is at the lower end of the projected ranges and climate variability about the mean varies little from the past, the projected impacts of climate change are likely to be reduced or delayed, and continued adaptation and technological development are likely to reduce the projected impacts and costs of climate change within the United States. Even in this event, however, the long lifetimes of greenhouse gases already in the atmosphere and the momentum of the climate system are projected to cause climate to continue to change for more than a century. Conversely, if the changes in climate are toward the upper end of the projected ranges and occur rapidly or lead to unprecedented conditions, the level of disruption is likely to be increased. Because of the momentum in the climate system and natural climate variability, adapting to a changing climate is inevitable. The question is whether we adapt poorly or well. With either weak or strong warming, however, the U.S. economy should continue to grow, with impacts being reduced if actions are taken to prepare for and adapt to future changes.

Although successful U.S. adaptation to the changing climate conditions during the 20th century provides some context for evaluating potential U.S. vulnerability to projected changes, the assessments indicate that the challenge of adaptation is likely to be greater during the 21st century than in the past. Natural ecosystems appear to be the most vulnerable to climate change because generally little can be done to help them adapt to the projected rate and amount of change. Sea level rise at mid-range rates is projected to cause additional loss of coastal wetlands, particularly in areas where there are obstructions to landward migration, and put coastal communities at greater risk of storm surges, especially in the southeastern United States. Reduced snowpack is very likely to alter the timing and amount of water supplies, potentially exacerbating water shortages, particularly throughout the western United States, if current water management practices cannot be successfully altered or modified. Increases in the heat index (which combines temperature and humidity) and in the frequency of heat waves are very likely. At a minimum, these changes will increase discomfort, particularly in cities; however, their health impacts can be ameliorated through such measures as the increased availability of air conditioning.

At the same time, greater wealth and advances in technologies are likely to help facilitate adaptation, particularly for human systems. In addition, highly managed ecosystems, such as crops and timber plantations, appear more robust than natural and lightly managed ecosystems, such as grasslands and deserts.

Some potential benefits were also identified in the assessments. For example, due to increased carbon dioxide (CO_2) in the atmosphere and an extended growing season, crop and forest productivities are likely to increase where water and nutrients are sufficient, at least for the next few decades. As a result, the potential exists for an increase in exports of some U.S. food products, depending on impacts in other food-growing regions around the world. Increases in crop production in fertile areas could cause prices to fall, benefiting consumers. Other potential benefits could include extended seasons for construction and warm-weather recreation, and reduced heating requirements and cold-weather mortality.

While most studies conducted to date have primarily had an internal focus, the United States also recognizes that its well-being is connected to the world through the global economy, the common global environment, shared resources, historic roots and continuing family relations, travel and tourism, migrating species, and more. As a result, in addition to internal impacts, the United States is likely to be affected, both directly and indirectly and both positively and detrimentally, by the potential consequences of climate change on the rest of the world. To better understand those potential consequences and the potential for adaptation worldwide, we are conducting and participating in research and assessments both within the United States and internationally (see Chapter 8). To alleviate vulnerability to adverse consequences, we are undertaking a wide range of activities that will help nationally and internationally, from developing medicines for dealing with infectious disease to promoting worldwide development through trade and assistance. As described in Chapter 7, the United States is also offering many types of assistance to the world community, believing that information about and preparation for climate change can help reduce adverse impacts.

INTRODUCTION

This chapter provides an overview of the potential impacts of climate change affecting the United States. The chapter also summarizes current measures and future adaptation and response options that are designed to increase resilience to climate variations and reduce vulnerability to climate change. The chapter is not intended to serve as a separate assessment in and of itself, but rather is drawn largely from analyses prepared for the U.S. National and IPCC Assessments, where more detailed consideration and specific references to the literature can be found (see NAST 2000, 2001 and IPCC 2001d, including the review of these results presented in NRC 2001a and IPCC 2001a).

As indicated by the findings presented here, considerable scientific progress has been made in gaining an understanding of the potential consequences of climate change. At the same time, considerable uncertainties remain because the actual impacts will depend on how emissions change, how the climate responds at global to regional scales, how societies and supporting technologies evolve, how the environment and society are affected, and how much ingenuity and commitment societies show in responding to the potential impacts. While the range of possible outcomes is very broad, all projections prepared by the IPCC (2001d) indicate that the anthropogenic contribution to global climate change will be greater during the 21st century than during the 20th century. Although the extents of climate change and its impacts nationally and regionally remain uncertain, it is generally possible to undertake "if this, then that" types of analyses. Such analyses can then be used to identify plausible impacts resulting from projected changes in climate and, in some cases, to evaluate the relative plausibility of various outcomes.

Clear and careful presentation of uncertainties is also important. Because the information is being provided to policymakers and because the limited scientific understanding of the processes involved generally precludes a fully quantitative analysis, extensive consideration led both the IPCC and the National Assessment experts to express their findings in terms of the relative likelihood of an outcome's occurring. To integrate the wide variety of information and to differentiate more likely from less likely outcomes, a common lexicon was developed to express the considered judgment of the National Assessment experts about the relative likelihood of the results. An advantage of this approach is that it moves beyond the vagueness of ill-defined terms, such as *may* or *might*, which allow an interpretation of the likelihood of an outcome's occurring to range from, for example, 1 to 99 percent, and so provide little basis for differentiating the most plausible from the least plausible outcomes.

In this chapter, which uses a lexicon similar to that developed for the National Assessment, the term *possible* is intended to indicate there is a finite likelihood of occurrence of a potential consequence, the term *likely* is used to indicate that the suggested impact is more plausible than other outcomes, and the term *very likely* is used to indicate that an outcome is much more plausible than other outcomes. Although the degree of scientific understanding regarding most types of outcomes is not complete, the judgments included here have been based on an evaluation of the consistency and extent of available scientific studies (e.g., field experiments, model simulations), historical trends, physical and biological relationships, and the expert judgment of highly qualified scientists actively engaged in relevant research (see NAST 2000, 2001). Because such judgments necessarily have a subjective component, the indications of relative likelihood may change as additional information is developed or as new approaches to adaptation are recognized.

Because this chapter is an overview, it generally focuses on types of outcomes that are at least considered *likely*, leaving discussion of the consequences of potential outcomes with lower likelihood to the more extensive scientific and assessment literature. However, it is important to recognize that there are likely to be unanticipated impacts of climate change that occur. Such "surprises," positive or negative, may stem from either (1) unforeseen changes in the physical climate system, such as major alterations in ocean circulation, cloud distribution, or storms; or (2) unpredicted biological consequences of these physical climate changes, such as pest outbreaks. For this reason, the set of suggested consequences presented here should not be considered comprehensive. In addition, unexpected social or economic changes, including major changes in wealth, technology, or political priorities, could affect society's ability to respond to climate change.

This chapter first describes the weather and climate context for the analysis of impacts, and then provides a summary of the types of consequences that are considered plausible across a range of sectors and regions. The chapter then concludes with a brief summary of actions being taken at the national level to learn more about the potential consequences of climate change and to encourage steps to reduce vulnerability and increase resilience to its impacts. Although the federal government can support research that expands understanding and the available set of options and that provides information about the potential consequences of climate change and viable response strategies, many of the adaptation measures are likely to be implemented at state and local levels and by the private sector. For these reasons and because of identified uncertainties, the results presented should not be viewed as definitive. Nonetheless, the more plausible types of consequences and impacts resulting from climate change and the types of steps that might be taken to reduce vulnerability and increase adaptation to climate variations and change are identified.

WEATHER AND CLIMATE CONTEXT

The United States experiences a wide variety of climate conditions. Moving across from west to east, the climates range from the semi-arid and arid climates of the Southwest to the continental climates of the Great Plains and the moister conditions of the eastern United States. North to south, the climates range from the Arctic climate of northern Alaska to the extensive forests of the Pacific Northwest to the tropical climates in Hawaii, the Pacific Islands, and the Caribbean. Although U.S. society and industry have largely adapted to the mean and variable climate conditions of their region, this has not been without some effort and cost. In addition, various extreme events each year still cause significant impacts across the nation. Weather events causing the most death, injury, and damage include hurricanes (or more generally tropical cyclones) and associated storm surges, lightning, tornadoes and other windstorms, hailstorms, severe winter storms, deep snow and avalanches, and extreme summer temperatures. Heat waves, floods, landslides, droughts, fires, land subsidence, coastal inundation and erosion, and even dam failures also can result when extremes persist over time.

To provide an objective and quantitative basis for an assessment of the potential consequences of climate change, the U.S. National Assessment was organized around the use of climate model scenarios that specified changes in the climate that might be experienced across the United States (NAST 2001). Rather than simply considering the potential influences of arbitrary changes in temperature, precipitation, and other variables, the use of climate model scenarios ensured that the set of climate conditions considered was internally consistent and physically plausible. For the National Assessment, the climate scenarios were primarily drawn from results available from the climate models developed and used by the United Kingdom's Hadley Centre and the Canadian Centre for Climate Modeling and Analysis. In addition, some analyses also drew on results from model simulations carried out at U.S. centers, including the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration's (NOAA's) Geophysical Fluid Dynamics Laboratory, and the National Aeronautics and Space Administration's (NASA's) Goddard Institute for Space Studies.

Use of these model results is not meant to imply that they provide accurate *predictions* of the specific changes in climate that will occur over the next 100 years. Rather, the models are considered to provide plausible *projections* of potential changes for the 21st century.[1] For some aspects of climate, all models, as well as other lines of evidence, are in agreement on the types of changes to be expected. For example, compared to changes during the 20th century, all climate model results suggest that warming during the 21st century across the country is very likely to be greater, that sea level and the heat index are going to rise more, and that precipitation is more likely to come in the heavier categories experienced in each region. Also, although there is not yet close agreement about how regional changes in climate can be expected to differ from larger-scale changes, the model simulations indicate some agreement in projections of the general seasonal and subcontinental patterns of the changes (IPCC 2001d).

This consistency has lent some confidence to these results. For some aspects of climate, however, the model results differ. For example, some models, including the Canadian model, project more extensive and frequent drought in the United States, while others, including the Hadley model, do not. As a result, the Canadian model suggests a hotter and drier Southeast during the 21st century, while the Hadley model suggests warmer and wetter conditions. Where such differences arise, the primary model scenarios provide two plausible, but different alternatives. Such differences proved helpful in exploring the particular sensitivities of various activities to uncertainties in the model results.

Projected Changes in the Mean Climate

The model scenarios used in the National Assessment project that the continuing growth in greenhouse gas emissions is likely to lead to annual-average warming over the United States that could be as much as several degrees Celsius (roughly 3–9ºF) during the 21st century. In addition, both precipitation and evaporation are projected to increase, and occurrences of unusual warmth and extreme wet and dry

[1] For the purposes of this chapter, *prediction* is meant to indicate forecasting of an outcome that will occur as a result of the prevailing situation and recent trends (e.g., tomorrow's weather or next winter's El Niño event), whereas *projection* is used to refer to potential outcomes that would be expected *if* some scenario of future conditions were to come about (e.g., concerning greenhouse gas emissions). In addition to uncertainties in how the climate is likely to respond to a changing atmospheric concentration, projections of climate change necessarily encompass a wide range because of uncertainties in projections of future emissions of greenhouse gases and aerosols and because of the potential effects of possible future agreements that might limit such emissions.

conditions are expected to become more frequent. For areas experiencing these changes, they would feel similar to an overall northern shift in weather systems and climate condition. For example, the central tier of states would experience climate conditions roughly equivalent to those now experienced in the southern tier, and the northern tier would experience conditions much like the central tier. Figure 6-1 illustrates how the summer climate of Illinois might change under the two scenarios. While the two models roughly agree on the amount of warming, the differences between them arise because of differences in projections of changing summertime precipitation.

Recent analyses indicate that, as a result of an uncertain combination of natural and human-induced factors, changes of the type that are projected for the 21st century were occurring to some degree during the 20th century. For example, over the last 100 years most areas in the contiguous United States warmed, although there was cooling in the Southeast. Also, during the 20th century, many areas experienced more periods of very wet or very dry conditions, and most areas experienced more intense rainfall events. While warming over the 48 contiguous states amounted to about 0.6ºC (about 1ºF), warming in interior Alaska was as much as 1.6ºC (about 3ºF), causing changes ranging from the thawing of permafrost to enhanced coastal erosion resulting from melting of sea ice.

Model simulations project that minimum temperatures are likely to continue to rise more rapidly than maximum temperatures, extending the trend that started during the 20th century. Although winter temperatures are projected to increase somewhat more rapidly than summer temperatures, the summertime heat index is projected to rise quite sharply because the rising absolute humidity will make summer conditions feel much more uncomfortable, particularly across the southern and eastern United States.

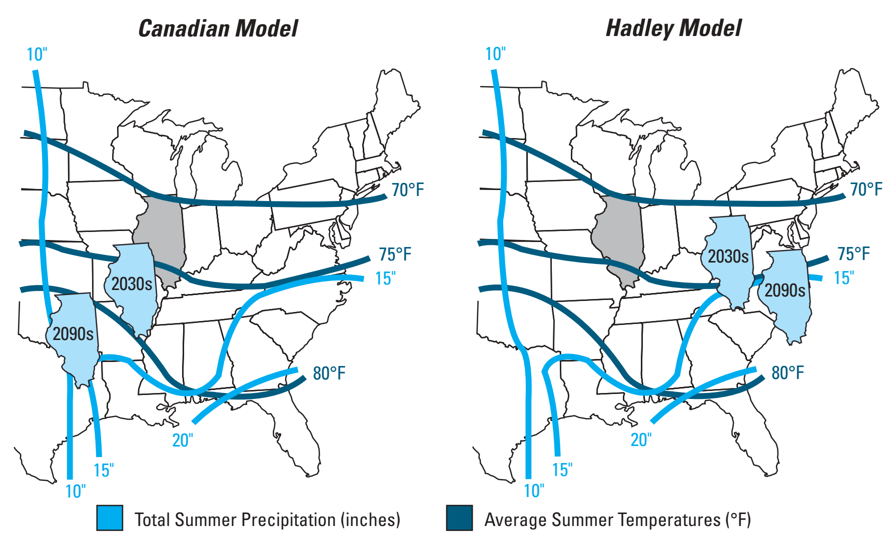
Although a 0.6ºC (1ºF) warming may not seem large compared to daily variations in temperature, it caused a decline of about two days per year in the number of days that minimum temperatures fell below freezing. Across the United States, this change was most apparent in winter and spring, with little change in autumn. The timing of the last spring frost changed similarly, with earlier cessation of spring frosts contributing to a lengthening of the frost-free season over the country. Even these seemingly small temperature-related changes have had some effects on the natural environment, including shorter duration of lake ice, a northward shift in the distributions of some species of butterflies, changes in the timing of bird migrations, and a longer growing season.

With respect to changes in precipitation, observations for the 20th century indicate that total annual precipitation has been increasing, both worldwide and over the country. For the contiguous United States, total annual precipitation increased by an estimated 5–10 percent over the past 100 years. With the exception of localized decreases in parts of the upper Great Plains, the Rocky Mountains, and Alaska, most regions experienced greater precipitation (Figure 6-2). This increased precipitation is evident in daily precipitation rates and in the number of rain days. It has caused widespread increases in stream flow for all levels of flow conditions, particularly during times of low to moderate flow conditions—changes that have generally improved water resource conditions and have reduced situations of hydrologic drought.

For the 21st century, models project a continuing increase in global precipitation, with much of the increase occurring in middle and high latitudes. The models also suggest that the increases are likely to be evident in rainfall events that, based on conditions in each region, would be considered heavy

FIGURE 6-1 Potential Effects of 21st-Century Warming on the Summer Climate of Illinois

This schematic illustrates how the summer climate of Illinois would shift under two plausible climate scenarios. Under the Canadian Climate Centre model's hot-dry climate scenario, the changes in summertime temperature and precipitation in Illinois would resemble the current climatic conditions in southern Missouri by the 2030s and in Oklahoma by the 2090s. For the warm-moist climate scenario projected by U.K.'s Hadley Centre model, summer in Illinois would become more like current summer conditions in the central Appalachians by the 2030s and North Carolina by the 2090s. Both shifts indicate warming of several degrees, but the scenarios differ in terms of projected changes in precipitation.



Note: The baseline climatic values are for the period 1961–90.

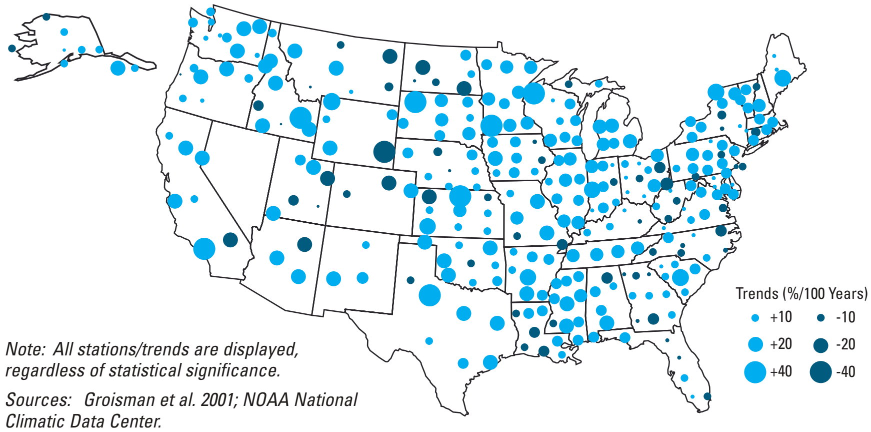
Source: D.J. Wuebbles, University of Illinois Urbana-Champaign, as included in NAST 2000.

(Figure 6-3). However, estimates of the regional pattern of changes vary significantly. While there are some indications that wintertime precipitation in the southwestern United States is likely to increase due to warming of the Pacific Ocean, changes across key U.S. forest and agricultural regions remain uncertain.

Soil moisture is critical for agriculture, vegetation, and water resources. Projections of changes in soil moisture depend on precipitation and runoff; changes in the timing and form of the precipitation (i.e., rain or snow); and changes in water loss by evaporation, which in turn depends on temperature change, vegetation, and the effects of changes in CO_2 concentration on evapotranspiration. As a result of the many interrelationships, projections

FIGURE 6-2 Observed Changes in Precipitation: 1901–1998

The geographical pattern of observed changes in U.S. annual precipitation during the 20th century indicates that, although local variations are occurring, precipitation has been increasing in most regions. The results are based on data from 1,221 Historical Climatology Network stations. These data are being used to derive estimates of a 100-year trend for each U.S. climate division.

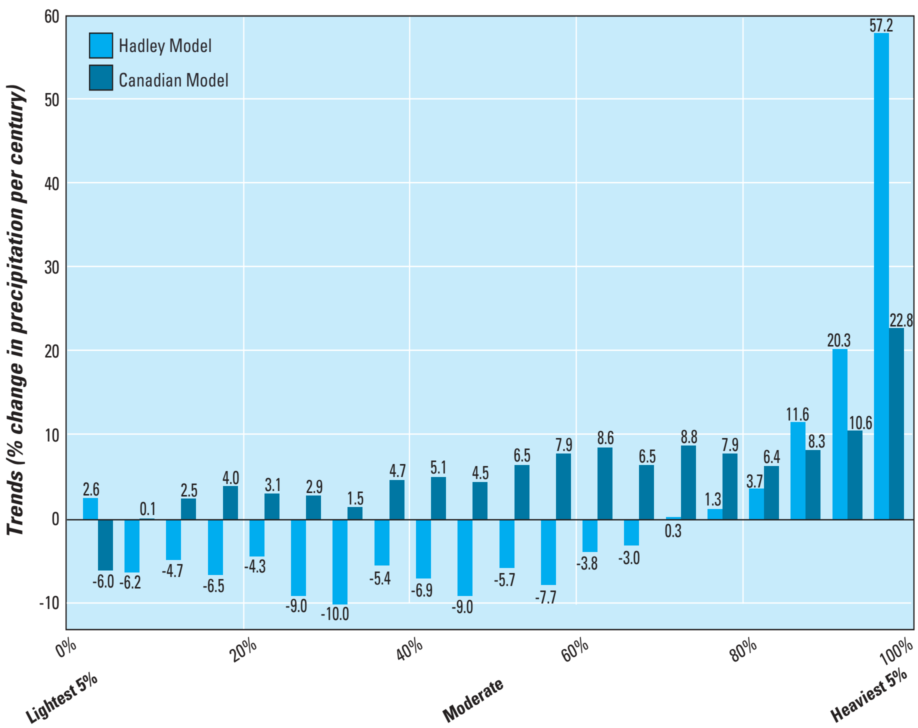


Note: All stations/trends are displayed, regardless of statistical significance.

Sources: Groisman et al. 2001; NOAA National Climatic Data Center.

FIGURE 6-3 Projected Changes in the Intensity of U.S. Precipitation for the 21st Century

The projected changes in precipitation over the United States as calculated by two models indicate that most of the increase is likely to occur in the locally heaviest categories of precipitation. Each bar represents the percentage change of precipitation in a different category of storm intensity. For example, the two bars on the far right indicate that the Canadian Centre model projects an increase of over 20 percent in the 5 percent most intense rainfall events in each region, whereas the Hadley Centre model projects an increase of over 55 percent in such events. Because both historic trends and future projections from many global climate models indicate an increase in the fraction of precipitation occurring during the heaviest categories of precipitation events in each region, a continuation of this trend is considered likely. Although this does not necessarily translate into an increase in flooding, higher river flows are likely to be a consequence.



Source: Byron Gleason, NOAA National Climatic Data Center (updated from NAST 2000).

remain somewhat uncertain of how changes in precipitation are likely to affect soil moisture and runoff, although the rising summertime temperature is likely to create additional stress by significantly increasing evaporation.

As in other highly developed nations, U.S. communities and industries have made substantial efforts to reduce their vulnerability to normal weather and climate fluctuations. However, adaptation to potential changes in weather extremes and climate variability is likely to be more difficult and costly. Unfortunately, projections of such changes remain quite uncertain, especially because variations in climate differentially affect different regions of the country. Perhaps the best-known example of a natural variation of the climate is caused by the El Niño–Southern Oscillation (ENSO), which is currently occurring every several years. ENSO has reasonably well-established effects on seasonal climate conditions across the country. For example, in the El Niño phase, unusually high sea-surface temperatures (SSTs) in the eastern and central equatorial Pacific act to suppress the occurrence of Atlantic hurricanes (Figure 6-4) and result in higher-than-average wintertime precipitation in the southwestern and southeastern United States, and in above-average temperatures in the Midwest (Figure 6-5). During a strong El Niño, effects can extend into the northern Great Plains.

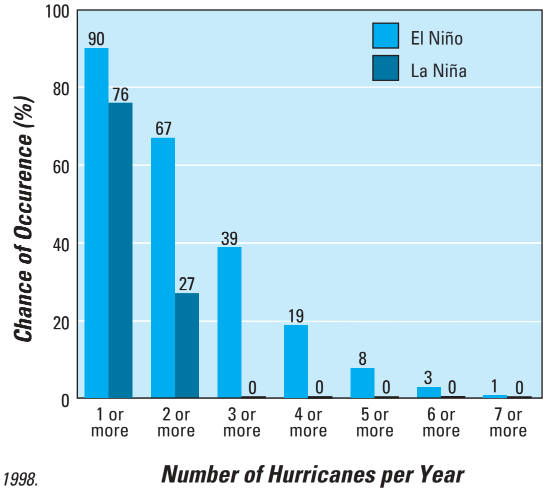
During the La Niña phase, which is characterized by unusually low SSTs off the west coast of South America, higher-than-average wintertime temperatures prevail across the southern half of the United States, more hurricanes occur in the tropical Atlantic, and more tornadoes occur in the Ohio and Tennessee valleys (Figures 6-4 and 6-5). During the summer, La Niña conditions can contribute to the occurrence of drought in the eastern half of the United States.

Projected Changes in Climate Variability

Other factors that affect the interannual variability of the U.S. climate include the Pacific Decadal Oscillation

FIGURE 6-4 Likelihood of Hurricanes to Strike the United States Based on El Niño and La Niña Occurrence

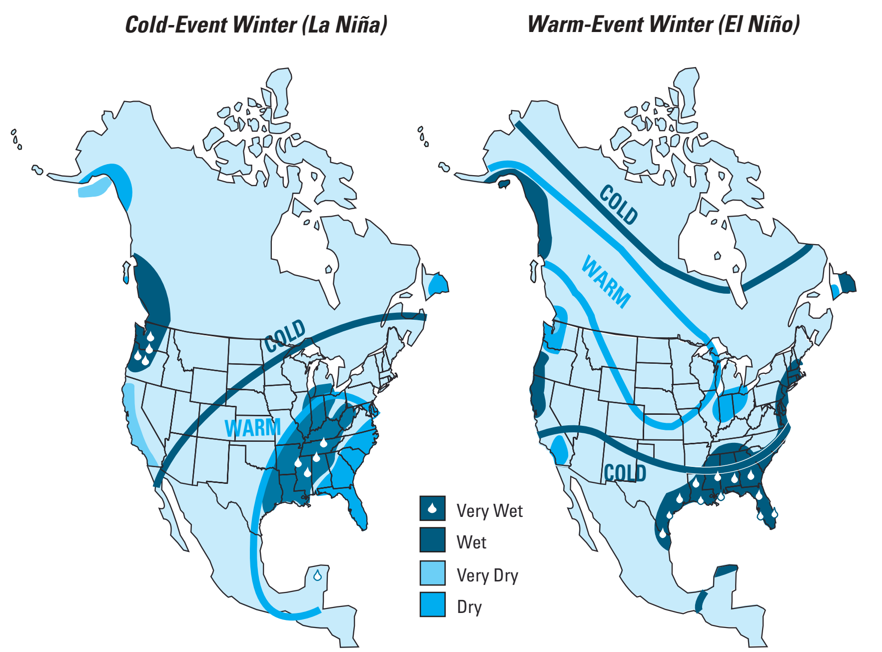
The frequency at which various numbers of hurricanes struck the United States during the 20th century has been found to depend on whether El Niño or La Niña events were occurring. Because of this observed relationship, changes in the frequency and intensity of these events are expected to affect the potential for damaging hurricanes striking the United States.



Source: Bove et al. 1998.

FIGURE 6-5 Climatic Tendencies across North America during El Niño and La Niña Events

Temperature and precipitation across North America have tended to vary from normal wintertime conditions as a result of El Niño (warmer-than-normal) and La Niña (colder-than-normal) events in the equatorial eastern Pacific Ocean. For many regions, the state of ocean temperatures in the equatorial Pacific Ocean has been found to be the most important determinant of whether winter conditions are relatively wet or dry, or relatively warm or cold. For example, winters in the Southeast tend to be generally cool and wet during El Niño (warm) events, and warm and dry during La Niña (cold) events.



Source: Florida State University, Center for Ocean–Atmospheric Prediction Studies. <http://www.coaps.fsu.edu>

(PDO) and the North Atlantic Oscillation (NAO).

The PDO is a phenomenon similar to ENSO, but is most apparent in the SSTs of the North Pacific Ocean. The PDO has a periodicity that is on the order of decades and, like ENSO, has two distinct phases—a warm phase and a cool phase. In the warm phase, oceanic conditions lead to an intensification of the storm-generating Aleutian Low, higher-than-average winter temperatures in the Pacific Northwest, and relatively high SSTs along the Pacific Coast. The PDO also leads to dry winters in the Pacific Northwest, but wetter conditions both north and south of there. Essentially, the opposite conditions occur during the cool phase.

The NAO is a phenomenon that displays a seesaw in temperatures and atmospheric pressure between Greenland and northern Europe. However, the NAO also includes effects in the United States. For example, when Greenland is warmer than normal, the eastern United States is usually colder, particularly in winter, and vice-versa.

Given these important and diverse interactions, research is being intensified to improve model simulations of natural climate variations, especially to improve projections of how such variations are likely to change. Although projections remain uncertain, the climate model of the Max Planck Institute in Germany, which is currently considered to provide the most realistic simulation of the ENSO cycle, calculates stronger and wider swings between El Niño and La Niña conditions as the global climate warms (Timmermann et al. 1999), while other models simply project more El Niño-like conditions over the eastern tropical Pacific Ocean (IPCC 2001d). Either type of result would be likely to cause important climate fluctuations across the United States.

Using the selected model scenarios as guides, but also examining the potential consequences of a continuation of past climate trends and of the possibility of exceeding particular threshold conditions, the National Assessment focused its analyses on evaluating the potential environmental and societal consequences of the climate changes projected for the 21st century, as described in the next section.

POTENTIAL CONSEQUENCES OF AND ADAPTATION TO CLIMATE CHANGE

Since the late 1980s, an increasing number of studies have been undertaken to investigate the potential impacts of climate change on U.S. society and the environment (e.g., U.S. EPA 1989, U.S. Congress 1993) and as components of international assessments (e.g., IPCC 1996a, 1998). While these studies have generally indicated that many aspects of the U.S. environment and society are likely to be sensitive to changes in climate, they were unable to provide in-depth perspectives of how various types of impacts might evolve and interact. In 1997, the interagency U.S. Global Change Research Program (USGCRP) initiated a National Assessment process to evaluate and synthesize available information about the potential impacts of climate change for the United States, to identify options for adapting to climate change, and to summarize research needs for improving knowledge about vulnerability, impacts, and adaptation (see Chapter 8). The findings were also undertaken to provide a more in-depth analysis of the potential time-varying consequences of climate change for consideration in scheduled international assessments (IPCC 2001a) and to contribute to fulfilling obligations under sections 4.1(b) and (e) of the United Nations Framework Convention on Climate Change.

The U.S. National Assessment was carried out recognizing that climate change is only one among many potential stresses that society and the environment face, and that, in many cases, adaptation to climate change can be accomplished in concert with efforts to adapt to other stresses. For example, climate variability and change will interact with such issues as air and water pollution, habitat fragmentation, wetland loss, coastal erosion, and reductions in fisheries in ways that are likely to compound these stresses. In addition, an aging national populace and rapidly growing populations in cities, coastal areas, and across the South and West are social factors that interact with and in some ways can increase the sensitivity of society to climate variability and change. In both evaluating potential impacts and developing effective responses, it is therefore important to consider interactions among the various stresses.

In considering the potential impacts of climate change, however, it is also important to recognize that U.S. climate conditions vary from the cold of an Alaskan winter to the heat of a Texas summer, and from the year-round near-constancy of temperatures in Hawaii to the strong variations in North Dakota. Across this very wide range of climate conditions and seasonal variation, American ingenuity and resources have enabled communities and businesses to develop, although particular economic sectors in particular regions can experience losses and disruptions from extreme conditions of various types. For example, the amount of property damage from hurricanes has been rising, although this seems to be mainly due to increasing development and population in vulnerable coastal areas. On the other hand, the number of deaths each year from weather extremes and from climatically dependent infectious diseases has been reduced sharply compared to a century ago, and total deaths relating to the environment are currently very small in the context of total deaths in the United States, even though the U.S. population has been rising. In addition, in spite of climate change, the productivity of the agriculture and forest sectors has never been higher and continues to rise, with excess production helping to meet global demand.

This adaptation to environmental variations and extremes has been accomplished because the public and private sectors have applied technological change and knowledge about fluctuating climate to implement a broad series of steps that have enhanced resilience and

Key National Findings Adapted from the U.S. National Assessment

Increased warming is projected for the 21st century—Assuming continued growth in world greenhouse gas emissions, the primary climate models drawn upon for the analyses carried out in the U.S. National Assessment projected that temperatures in the contiguous United States will rise 3–5°C (5–9°F) on average during the 21st century. A wider range of outcomes, including a smaller warming, is also possible.

Impacts will differ across regions—Climate change and its potential impacts are likely to vary widely across the country. Temperature increases are likely to vary somewhat among regions. Heavy precipitation events are projected to become more frequent, yet some regions are likely to become drier.

Ecosystems are especially vulnerable—Many ecosystems are highly sensitive to the projected rate and magnitude of climate change, although more efficient water use will help some ecosystems. A few ecosystems, such as alpine meadows in the Rocky Mountains and some barrier islands, are likely to disappear entirely in some areas. Other ecosystems, such as southeastern forests, are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests. Some of the goods and services lost through the disappearance or fragmentation of natural ecosystems are likely to be costly or impossible to replace.

Widespread water concerns arise—Water is an issue in every region, but the nature of the vulnerabilities varies. Drought is an important concern virtually everywhere. Floods and water quality are concerns in many regions. Snowpack changes are likely to be especially important in the West, Pacific Northwest, and Alaska.

Food supply is secure—At the national level, the agriculture sector is likely to be able to adapt to climate change. Mainly because of the beneficial effects of the rising carbon dioxide levels on crops, overall U.S. crop productivity, relative to what is projected in the absence of climate change, is very likely to increase over the next few decades. However, the gains are not likely to be uniform across the nation. Falling prices are likely to cause difficulty for some farmers, while benefiting consumers.

Near-term forest growth increases—Forest productivity is likely to increase over the next several decades in some areas as trees respond to higher carbon dioxide levels by increasing water-use efficiency. Such changes could result in ecological benefits and additional storage of carbon. Over the longer term, changes in larger-scale processes, such as fire, insects, droughts, and disease, could decrease forest productivity. In addition, climate change is likely to cause long-term shifts in forest species, such as sugar maples moving north out of the country.

Increased damage occurs in coastal and permafrost areas—Climate change and the resulting rise in sea level are likely to exacerbate threats to buildings, roads, power lines, and other infrastructure in climate-sensitive areas. For example, infrastructure damage is expected to result from permafrost melting in Alaska and from sea level rise and storm surges in low-lying coastal areas.

Adaptation determines health outcomes—A range of negative health impacts is possible from climate change. However, as in the past, adaptation is likely to help protect much of the U.S. population. Maintaining our nation's public health and community infrastructure, from water treatment systems to emergency shelters, will be important for minimizing the impacts of water-borne diseases, heat stress, air pollution, extreme weather events, and diseases transmitted by insects, ticks, and rodents.

Other stresses are magnified by climate change—Climate change is very likely to modify the cumulative impacts of other stresses. While it may magnify the impacts of some stresses, such as air and water pollution and conversion of habitat due to human development patterns, it may increase agricultural and forest productivity in some areas. For coral reefs, the combined effects of increased CO_2 concentration, climate change, and other stresses are very likely to exceed a critical threshold, causing large, possibly irreversible impacts.

Uncertainties remain and surprises are expected—Significant uncertainties remain in the science underlying regional changes in climate and their impacts. Further research would improve understanding and capabilities for projecting societal and ecosystem impacts. Increased knowledge would also provide the public with additional useful information about options for adaptation. However, it is likely that some aspects and impacts of climate change, both positive and negative, will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.

Sources: NAST 2000, 2001.

reduced vulnerability. For example, these steps have ranged from better design and construction of buildings and communities to greater availability of heating in winter and cooling in summer, and from better warnings about extreme events to advances in public health care. Because of this increasing resilience to climate variations and relative success in adapting to the modest changes in climate that were observed during the 20th century, information about likely future climate changes and continuing efforts to plan for and adapt to these changes are likely to prove useful in minimizing future impacts and preparing to take advantage of the changing conditions.

With these objectives in mind, the U.S. National Assessment process, which is described more completely in Chapter 8, initiated a set of regional, sectoral, and national activities. This page presents an overview of key national findings, and the following subsections elaborate on these findings, covering both potential consequences and the types of adaptive steps that are underway or could be pursued to moderate or deal with adverse outcomes. The subsections summarize the types of impacts that are projected, covering initially the potential impacts on land cover; then the potential impacts on agriculture, forest, and water resources, which are key natural resource sectors on which society depends; then potential impacts associated with coastal regions and human health that define the environment in which people live; and finally summarization of the primary issues that are specific to particular U.S. regions. A full list of regional, sectoral, and national reports prepared under the auspices of the U.S. National Assessment process and additional materials relating to research and assessment activities can be found at http://www.usgcrp.gov.

Potential Interactions with Land Cover

The natural vegetative cover of the United States is largely determined by the prevailing climate and soil. Where not altered by societal activities, climate conditions largely determine where individual species of plants and animals can live, grow, and reproduce. Thus, the collections of species that we are familiar with—e.g., the southeastern mixed deciduous forest, the desert ecosystems of the arid Southwest, the productive grasslands of the Great Plains—are primarily a consequence of present climate conditions. Past changes in ecosystems indicate that some species are so strongly influenced by the climate to which they are adapted that they are vulnerable even to modest changes in climate. For example, alpine meadows at high elevations in the West exist where they do entirely because the plants that comprise them are adapted to cold conditions that are too harsh for other species in the region. The desert vegetation of the Southwest is adapted to the region's high summer temperatures and aridity. Similarly, the forests in the East tend to have adapted to relatively high rainfall and soil moisture; if drought conditions were to persist, grasses and shrubs could begin to out-compete tree seedlings, leading to completely different ecosystems.

To provide a common base of information about potential changes in vegetation across the nation for use in the National Assessment (NAST 2000), specialized ecosystem models were used to evaluate the potential consequences of climate change and an increasing CO_2 concentration for the dominant vegetation types. Biogeography models were used to simulate potential shifts in the geographic distribution of major plant species and communities (ecosystem structure). And biogeochemistry models were used to simulate changes in basic ecosystem processes, such as the cycling of carbon, nutrients, and water (ecosystem function). Each type of model was used in considering the potential consequences of the two primary model-based climate scenarios. These scenarios represented conditions across much of the United States that were generally either warmer and moister, or hotter and drier. The results from both types of models indicated that changes in ecosystems would be likely to be significant.

Climate changes that affect the land surface and terrestrial vegetation will also have implications for fresh-water and coastal marine ecosystems that depend on the temperature of runoff water, on the amount of erosion, and on other factors dependent on the land cover. For example, in aquatic ecosystems, many fish can breed only in water that falls within a narrow range of temperatures. As a result, species of fish that are adapted to cool waters can quickly become unable to breed successfully if water temperatures rise. As another example, because washed-off soil and nutrients can benefit wetland species (within limits) and harm estuarine ecosystems, changes in the frequency or intensity of runoff events caused by changes in land cover can be important. Such impacts are described in the subsections dealing with climate change interactions with water resources and the coastal environment, while issues affecting terrestrial land cover are covered in the following subsection.

Redistribution of Land Cover

The responses of ecosystems to projected changes in climate and CO_2 are made up of the individual responses of their constituent species and how they interact with each other. Species in current ecosystems can differ substantially in their tolerances to changes in temperature and precipitation, and in their responses to changes in the CO_2 concentration. As a result, the ranges of individual species are likely to shift at different rates, and different species are likely to have different degrees of success in establishing themselves in new locations and environments. While changes in climate projected for the coming hundred years are very likely to alter current ecosystems, projecting these kinds of biological and ecological responses and the structure and functioning of the new plant communities is very difficult.

Analyses of present ecosystem distributions and of past shifts indicate that natural ecosystems are sensitive to changes in surface temperature, precipitation patterns, and other climate parameters and changes in the atmospheric CO_2 concentration. For example, changes in temperature and precipitation of the magnitude being projected are likely to cause shifts in the areas occupied by dominant vegetation types relative to their current distribution. Some ecosystems that are already constrained by climate, such as alpine meadows in the Rocky Mountains, are likely to face extreme stress and disappear entirely in some places. Other more widespread ecosystems are also likely to be sensitive to climate change. For example, both climate model scenarios suggest that the southwestern United States will become moister, allowing more vegetation to grow (Figure 6-6). Such a change is likely to transform desert landscapes into grasslands or shrublands, altering both their potential use and the likelihood of fire. In the northeastern United States, both climate scenarios suggest changes mainly in the species composition of the forests, including the northward displacement of sugar maples, which could lead to loss in some areas. However, the studies also indicate that conditions in this region will remain conducive to maintaining a forested landscape, mainly oak and hickory. In the southeastern United States, however, there was less agreement among the models: the hot-dry climate scenario was projected to lead to conditions that would be conducive to the potential breakup of the forest landscape into a mosaic of forests, savannas, and grasslands; in contrast, the warm-moist scenario was projected to lead to a northward expansion of the southeastern mixed forest cover. (See additional discussion in the Forest subsection.)

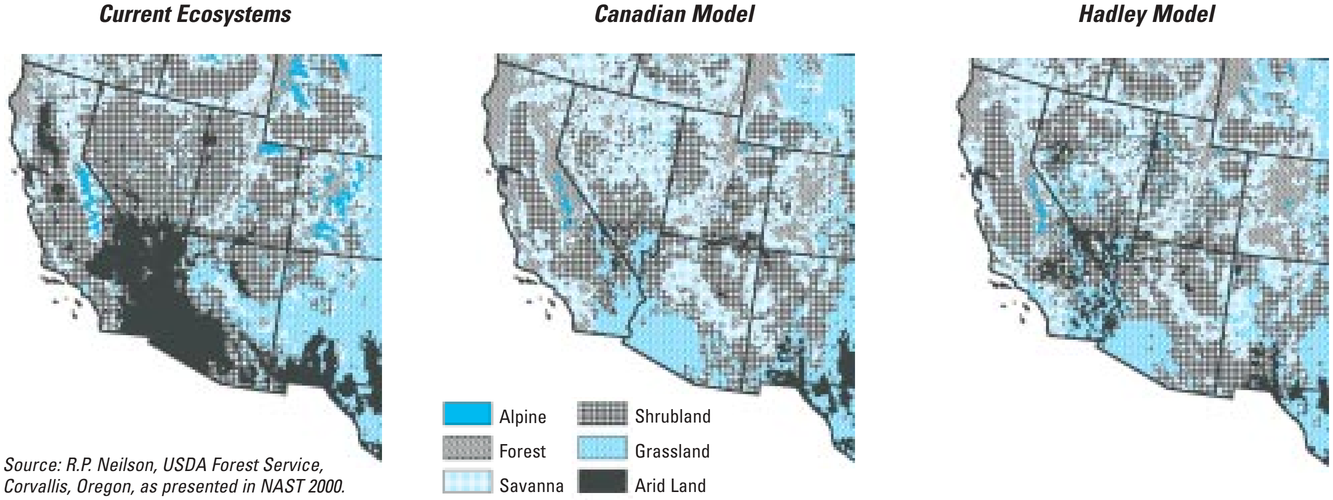
Basically, changes in land cover were projected to occur, at least to some degree, in all locations, and these changes cannot generally be prevented if the climate changes and vegetation responds as much as projected.

Effects on the Supply of Vital Ecosystem Goods and Services

In addition to the value of natural ecosystems in their own right, ecosystems of all types, from the most natural

FIGURE 6-6 **Potential Effects of Projected Climate Change on Ecosystem Distribution**

Both the Hadley and the Canadian models project increasing wintertime precipitation in the U.S. Southwest toward the end of the 21st century and a conversion of desert ecosystems to shrub and grassland ecosystems.



Source: R.P. Neilson, USDA Forest Service, Corvallis, Oregon, as presented in NAST 2000.

to the most extensively managed, provide a variety of goods and services that benefit society. Some products of ecosystems enter the market and contribute directly to the economy. For example, forests serve as sources of timber and pulpwood, and agro-ecosystems serve as sources of food. Ecosystems also provide a set of unpriced services that are valuable but that typically are not traded in the marketplace. Although there is no current market, for example, for the services that forests and wetlands provide for improving water quality, regulating stream flow, providing some measure of protection from floods, and sequestering carbon, some of these services are very valuable to society. Ecosystems are also valued for recreational, aesthetic, and ethical reasons. For example, the bird life of the coastal marshes of the Southeast and the brilliant autumn colors of the New England forests are treasured components of the nation's regional heritages and important elements of our quality of life.

Based on the studies carried out, changes in land cover induced by climate change, along with an increased level of disturbances, could have varied impacts on ecosystem services, including the abilities of ecosystems to cleanse the air and water, stabilize landscapes against erosion, and store carbon. Even in such regions as the Southwest, where vegetation is expected to increase as a result of increased rainfall and enhanced plant growth due to the rising CO_2 concentration, an important potential consequence is likely to be a heightened frequency and intensity of fires during the prolonged summer season. Increased fire frequency would likely be a threat not only to the natural land cover, but also to the many residential structures being built in vulnerable suburban and rural areas, and later would increase vulnerability to mudslides as a result of denuded hills. Considering the full range of available results, it is plausible that climate change-induced alterations to natural ecosystems could affect the availability of some ecosystem goods and services.

Effects of an Increased CO_2 Concentration on Plants

The ecosystem models used in the National Assessment considered the potential effects of increases in the atmospheric CO_2 concentration because the CO_2 concentration affects plant species via a direct physiological effect on photosynthesis (the process by which plants use CO_2 to create new biological material). Higher CO_2 concentrations generally enhance plant growth if the plants also have sufficient water and nutrients (such as nitrogen) that are needed to sustain this enhanced growth. For example, the CO_2 level in commercial greenhouses is sometimes boosted to stimulate plant growth. In addition to enhancing plant growth, higher CO_2 levels can raise the efficiency with which plants use water and reduce their susceptibility to damage by air pollutants.

As a result of these various influences, different types of plants respond at different rates to increases in the atmospheric CO_2 concentration, resulting in a divergence of growth rates. Most species grow faster and increase biomass; however, the nutritional value of some of these plants could be altered. Both because of biochemical processing and because warming temperatures increase plant respiration, the beneficial effects of increased CO_2 on plants are also projected to flatten at some higher level of CO_2 concentration, beyond which continuing increases in the CO_2 concentration would not enhance plant growth.

While there is still much to be learned about the CO_2 "fertilization" effect, including its limits and its direct and indirect implications, many ecosystems are projected to benefit from a higher CO_2 concentration, and plants will use water more efficiently.

Effects on Storage of Carbon

In response to changes in climate and the CO_2 concentration, the biogeochemistry models used in the National Assessment generally simulated increases in the amount of carbon stored in vegetation and soils for the continental United States. The calculated increases were relatively small, however, and not uniform across the country. For example, one of the biogeochemistry models, when simulating the effects of hotter and drier conditions, projected that the southeastern forests would lose more carbon by respiration than they would gain by increased photosynthesis, causing an overall carbon loss of up to 20 percent by 2030. Such a loss would indicate that the forests were in a state of decline. The same biogeochemistry model, however, when calculating the potential effects of the warmer and moister climate scenario, projected that forests in the same part of the Southeast would likely gain between 5 and 10 percent in carbon over the next 30 years, suggesting a more vigorous forest.

Susceptibility of Ecosystems to Disturbances

Prolonged stress due to insufficient soil moisture can make trees more susceptible to insect attack, lead to plant death, and increase the probability of fire as dead plant material adds to an ecosystem's "fuel load." The biogeography models used in this analysis simulated at least part of this sequence of climate-triggered events in ecosystems as a prelude to calculating shifts in the geographic distribution of major plant species.

For example, one of the biogeography models projected that a hot, dry climate in the Southeast would be likely to result in the replacement of the current mixed evergreen and deciduous forests by savanna/woodlands and grasslands, with much of the change effected by an increased incidence of fire. Yet the same biogeography model projected a slight northward expansion of the mixed evergreen and deciduous forests of the Southeast in response to the warm, moist climate scenario, with no significant contraction along the southern boundary. Thus, in this region, changes in the frequency and intensity of such disturbances as fire are likely to be major determinants of the type and rapidity of the conversion of the land cover to a new state.

As explained more fully in the sections on the interactions of climate change with coastal and water resources, aquatic ecosystems are also likely to be affected by both climate change and unusual disturbances, such as storms and storm surges.

Potential Adaptation Options to Preserve Prevailing Land Cover

The National Assessment concluded that the potential vulnerability of natural ecosystems is likely to be more important than other types of potential impacts affecting the U.S. environment and society. This importance arises because in many cases little can be done to help these ecosystems adapt to the projected rate and amount of climate change. While adjustments in how some systems are managed can perhaps reduce the potential impacts, the complex, interdependent webs that have been naturally generated over very long periods are not readily shifted from one place to another or easily recreated in new locations, even to regions of similar temperature and moisture. Although many regions have experienced changes in ecosystems as a result of human-induced changes in land cover, and people have generally become adapted to—and have even become defenders of—the altered conditions (e.g., reforestation of New England), the climate-induced changes during the 21st century are likely to affect virtually every region of the country—both the ecosystems where people live, as well as those in the protected areas that have been created as refuges against change.

Potential Interactions with Agriculture

U.S. croplands, grassland pasture, and range occupy about 420 million hectares (about 1,030 million acres), or nearly 55 percent of the U.S. land area, excluding Alaska and Hawaii (USDA/ERS 2000). Throughout the 20th century, agricultural production shifted toward the West and Southwest. This trend allowed regrowth of some forests and grasslands, generally enhancing wildlife habitats, especially in the Northeast, and contributing to sequestration of carbon in these regions.

U.S. food production and distribution comprise about 10 percent of the U.S. economy. The value of U.S. agricultural commodities (food and fiber) exceeds $165 billion at the farm level and over $500 billion after processing and marketing, Because of the productivity of U.S. agriculture, the United States is a major supplier of food and fiber for the world, accounting for more than 25 percent of total global trade in wheat, corn, soybeans, and cotton.

Changes in Agricultural Productivity

U.S. agricultural productivity has improved by over 1 percent a year since 1950, resulting in a decline in both production costs and commodity prices, limiting the net conversion of natural habitat to cropland, and freeing up land for the Conservation Reserve Program. Although the increased production and the two-thirds drop in real commodity prices have been particularly beneficial to consumers inside and outside the United States and have helped to reduce hunger and malnourishment around the world, the lower prices have become a major concern for producers and have contributed to the continuing decline in the number of small farmers across the country. Continuation of these trends is expected, regardless of whether climate changes, with continuing pressures on individual producers to further increase productivity and reduce production costs.

On the other hand, producers consider anything that might increase their costs relative to other producers or that might limit their markets as a threat to their economic well-being. Issues of concern include regulatory actions, such as efforts to control the off-site consequences of soil erosion, agricultural chemicals, and livestock wastes; extreme weather or climate events; new pests; and the development of pest resistance to existing pest control strategies.

Future changes in climate are expected to interact with all of these issues. In particular, although some factors may tend to limit growth in yields, rising CO_2 concentrations and continuing climate change are projected, on average, to contribute to extending the persistent upward trend in crop yields that has been evident during the second half of the 20th century. In addition, if all else remains equal, these changes could change supplies of and requirements for irrigation water, increase the need for fertilizers to sustain the gain in carbon production, lead to changes in surface-water quality, necessitate increased use of pesticides or other means to limit damage from pests, and alter the variability of the climate to which the prevailing agricultural sector has become accustomed. However, agricultural technology is currently undergoing rapid change, and future production technologies and practices seem likely to be able to contain or reduce these impacts.

Assuming that technological advances continue at historical rates, that there are no dramatic changes in federal policies or in international markets, that adequate supplies of nutrients are available and can be applied without exacerbating pollution problems, and that no prolonged droughts occur in major agricultural regions, U.S. analyses indicate that it is unlikely that climate change will imperil the ability of the United States to feed its population and to export substantial amounts of foodstuffs (NAAG 2002). These studies indicate that, at the national level, overall agricultural productivity is likely to increase as a result of changes in the CO_2 concentration and in climate projected for at least the next several decades. The crop models used in these studies assume that the CO_2 fertilization effect will be strongly beneficial and will also allow for a limited set of *on-farm* adaptation options, including changing planting dates and varieties, in res-ponse to the changing conditions. These adaptation measures contribute small additional gains in yields of dry-land crops and greater gains in yields of irrigated crops. However, analyses performed to date have neither considered all of the consequences of possible changes in pests, diseases, insects, and extreme events that may result, nor been able to consider the full range of potential adaptation options (e.g., genetic modification of crops to enhance resistance to pests, insects, and diseases).

Recognizing these limitations, available evaluations of the effects of anticipated changes in the CO_2 concentration and climate on crop production and yield and the adaptive actions by farmers generally show positive results for cotton, corn for grain and silage, soybeans, sorghum, barley, sugar beets, and citrus fruits (Figure 6-7). The productivity of pastures may also increase as a result of these changes. For other crops, including wheat, rice, oats, hay, sugar cane, potatoes, and tomatoes, yields are projected to increase under some conditions and decrease under others, as explained more fully in the agriculture assessment (NAAG 2002).

The studies also indicate that not all U.S. agricultural regions are likely to be affected to the same degree by the projected changes in climate that have been investigated. In general, northern areas, such as the Midwest, West, and Pacific Northwest, are projected to show large gains in yields, while influences on crop yields in other regions vary more widely, depending on the climate scenario and time period. For example, projected wheat yields in the southern Great Plains could decline if the warming is not accompanied by sufficient precipitation.

These analyses used market-scale economic models to evaluate the overall economic implications for various crops. These models allow for a wide range of adaptations in response to changing productivity, prices, and resource use, including changes in irrigation, use of fertilizer and pesticides, crops grown and the location of cropping, and a variety of other farm management options. Based on studies to date, unless there is inadequate or poorly distributed precipitation, the net effects of climate change on the agricultural segment of the U.S. economy over the 21st century are generally projected to be positive. These studies indicate that, economically, consumers are likely to benefit more from lower prices than producers suffer from the decline in profits. Complicating the analyses, however, the studies indicate that producer versus consumer effects will depend on how climate change affects production of these crops elsewhere in the world. For example, for crops grown in the United States, economic losses to farmers due to lower commodity prices are offset under some conditions by an increased advantage of U.S. farmers over foreign competitors, leading to an increased volume of exports.

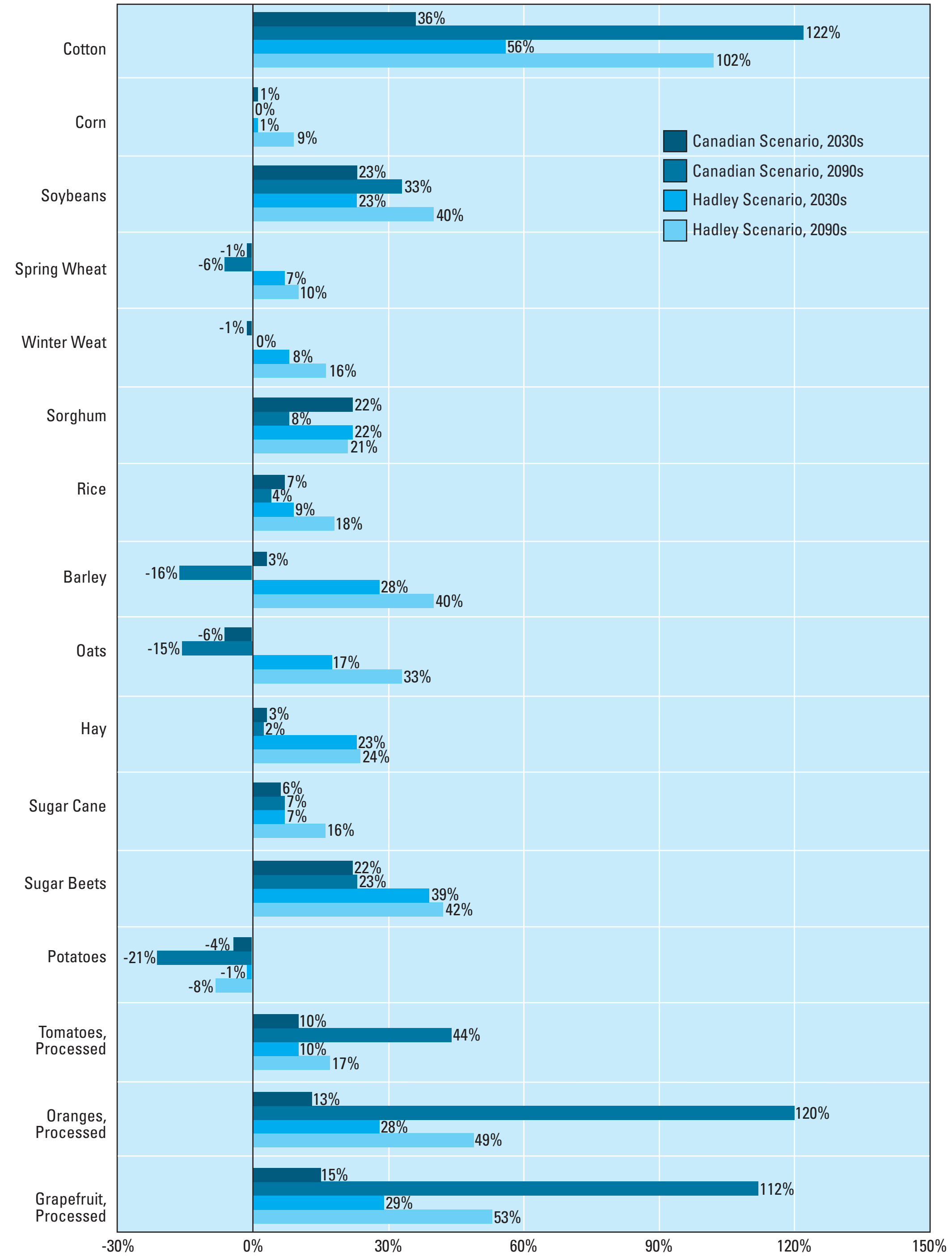
Because U.S. food variety and supplies depend not only on foodstuffs produced nationally, the net effect of climate change on foods available for U.S. consumers will also depend on the effects of climate change on global production of these foodstuffs. These effects will in turn depend not only on international markets, but also on how farmers around the world are able to adapt to climate change and other factors they will face. While there are likely to be many regional variations, experience indicates that research sponsored by the United States and other nations has played an important role in promoting the ongoing, long-term increase in global agricultural productivity. Further research, covering opportunities ranging from genetic design to improving the salt tolerance of key crops, is expected to continue to enhance overall global production of foodstuffs.

Changes in Water Demands by Agriculture

Within the United States, a key determinant of agricultural productivity will be the ongoing availability of sufficient water where and when it is

FIGURE 6-7 Effects of Potential Changes in Climate on U.S Crop Yields

Results for 16 crops, given as the percentage differences between future yields for two periods (2030s and 2090s) and current yields indicate that warmer climate conditions are likely to lead to increased yields for most crops. The results consider the physiological responses of the crops to future climate conditions under either dry-land or irrigated cultivation, assuming a limited set of reasonable adaptive response by producers. Climate scenarios are drawn from two different climate models that are likely to span the range of changes of future conditions, ranging from the warm-moist changes projected by the U.K.'s Hadley Centre model (version 2) to the hot-dry changes projected by the Canadian Climate Centre model. The most positive responses resulted when conditions were warmer and wetter in key growing regions (e.g., cotton), when frost occurrence was reduced (e.g., grapefruit), and when northern areas warmed (e.g., silage from pasture improvement).



Source: NAAG 2002.

needed. The variability of the U.S. climate has provided many opportunities for learning to deal with a wide range of climate conditions, and the U.S. regions where many crops are grown have changed over time without disrupting production. In addition, steps to build up the amount of carbon in soils—which is likely to be one component of any carbon mitigation program—will enhance the water-holding capacity of soils and decrease erosion and vulnerability to drought, thereby helping to improve overall agricultural productivity. For areas that are insufficiently moist, irrigation has been used to enhance crop productivity. In addition, about 27 percent of U.S. cultivated land is currently under reduced tillage. Several projects, such as the Iowa Soil Carbon Sequestration Project, that are underway to promote conservation tillage practices as a means to mitigate climate change will have the ancillary benefits of reducing soil erosion and runoff while increasing soil water and nitrogen retention.

Analyses conducted for the National Assessment project that climate change will lead to changes in the demand for irrigation water and, if water resources are insufficient, to changes in the crops being grown. Although regional differences will likely be substantial, model projections indicate that, on average for the nation, agriculture's need for irrigation water is likely to slowly decline. At least two factors are responsible for this projected reduction: (1) precipitation will increase in some agricultural areas, and (2) faster development of crops due to higher temperatures and an increased CO_2 concentration is likely to result in a shorter growing period and consequently a reduced demand for irrigation water. Moreover, a higher CO_2 concentration generally enhance a plant's water-use efficiency. These factors can combine to compensate for the increased transpiration and soil water loss due to higher air temperatures. However, a decreased period of crop growth also leads to decreased yields, although it may be possible to overcome this disadvantage through crop breeding.

Changes in Surface-Water Quality due to Agriculture

Potential changes in surface-water quality as a result of climate change is an issue that has only started to be investigated. For example, in recent decades, soil erosion and excess nutrient runoff from crop and livestock production have severely degraded Chesapeake Bay, a highly valuable natural resource. In simulations for the National Assessment, loading of excess nitrogen from corn production into Chesapeake Bay is projected to increase due to both the change in average climate conditions and the effects of projected changes in extreme weather events, such as floods or heavy downpours that wash large amounts of fertilizers and animal manure into surface waters. Across the country, changes in future farm practice (such as no-till or reduced-till agriculture) that enhance buildup and retention of soil moisture, and better matching of the timing of a crop's need for fertilizer with the timing of application are examples of approaches that could reduce projected adverse impacts on water quality. In addition, the potential for reducing adverse impacts of fertilizer application and soil erosion by using genetically modified crops has not yet been considered.

Changes in Pesticide Use by Agriculture

Climate change is projected to cause farmers in most regions to increase their use of pesticides to sustain the productivity of current crop strains. While this increase is expected to result in slightly poorer overall economic performance, this effect is minimal because pesticide expenditures are a relatively small share of production costs. Neither the potential changes in environmental impacts as a result of increased pesticide use nor the potential for genetic modification to enhance pest resistance have yet been evaluated.

Effects of Changes in Climate Variability on Agriculture

Based on experience, agriculture is also likely to be affected if the extent and occurrence of climate fluctuations and extreme events change. The vulnerability of agricultural systems to climate and weather extremes varies with location because of differences in soils, production systems, and other factors. Changes in the form (rain, snow, or hail), timing, frequency, and intensity of precipitation, and changes in wind-driven events (e.g., wind storms, hurricanes, and tornadoes) are likely to have significant consequences in particular regions. For example, in the absence of adaptive measures, an increase in heavy precipitation events seems likely in some areas to aggravate erosion, waterlogging of soils, and leaching of animal wastes, pesticides, fertilizers, and other chemicals into surface and ground water. Conversely, lower precipitation in other areas may reduce some types of impacts.

A major source of U.S. climate variability is the El Niño–Southern Oscillation (ENSO). The effects of ENSO events vary widely across the country, creating wet conditions in some areas and dry conditions in others that can have significant impacts on agricultural production. For example, over the past several decades, average corn yield has been reduced by about 15–30 percent in years with widespread floods or drought. Better prediction of such variations is a major focus of U.S. and international research activities (e.g., through the International Research Institute for Climate Prediction) because, in part, such information could increase the range of adaptive responses available to farmers. For example, given sufficient warning of climate anomalies (e.g., of conditions being warm and dry, cool and moist, etc.), crop species and crop planting dates could be optimized for the predicted variation, helping to reduce the adverse impact on yields and overall production. Because long-term projections suggest that ENSO variations may become even stronger as global average temperature increases, achieving even better predictive skill in the future will be especially important to efforts to maximize production in the face of climate fluctuations.

Potential Adaptation Strategies for Agriculture

To ameliorate the deleterious effects of climate change generally, such adaptation strategies as changing planting dates and varieties are likely to help to significantly offset economic losses and increase relative yields. Adaptive measures are likely to be particularly critical for the Southeast because of the large reductions in yields projected for some crops if summer precipitation declines. With the wide range of growing conditions across the United States, specific breeding for response to CO_2 is likely to be required to more fully benefit from the CO_2 fertilization effect detected in experimental crop studies. Breeding for tolerance to climatic stress has already been exploited, and varieties that do best under ideal conditions usually also out-perform other varieties under stress conditions.

Although many types of changes can likely be adapted to, some adaptations to climate change and its impacts may have negative secondary effects. For example, an analysis of the potential effects of climate change on water use from the Edward's aquifer region near San Antonio, Texas, found increased demand for ground-water resources. Increased water use from this aquifer would threaten endangered species dependent on flows from springs supported by the aquifer.

In addition, in the absence of genetic modification of available crop species to counter these influences, pesticide and herbicide use is likely to increase with warming. Greater chemical inputs would be expected to increase the potential for chemically contaminated runoff reaching prairie wetlands and ground water, which, if not controlled by on-site measures, could pollute rivers and lakes, drinking-water supplies, coastal waters, recreation areas, and waterfowl habitat.

As in the past, farmers will need to continue to adapt to the changing conditions affecting agriculture, and changing climate is likely to become an increasingly influential factor. Presuming adaptation to changing climate conditions is successful, the U.S. agricultural sector should remain strong—growing more on less land while continuing to lower prices for the consumer, exporting large amounts of food to help feed the world, and storing carbon to enhance resilience to drought and contribute to the slowing of climate change.

Potential Interactions with Forests

Forests cover nearly one-third of the United States, providing wildlife habitat; clean air and water; carbon storage; and recreational opportunities, such as hiking, camping, and fishing. In addition, harvested products include timber, pulpwood, fuelwood, wild game, ferns, mushrooms, berries, and much more. This wealth of products and services depends on forest productivity and biodiversity, which are in turn strongly influenced by climate.

Across the country, native forests are adapted to the local climates in which they developed, such as the cold-tolerant boreal forests of Alaska, the summer drought-tolerant forests of the Pacific Northwest, and the drought-adapted piñon-juniper forests of the Southwest. Given the overall importance of the nation's forests, the potential impacts from climate change are receiving close attention, although it is only one of several factors meriting consideration.

A range of human activities causes changes in forests. For example, significant areas of native forests have been converted to agricultural use, and expansion of urban areas has fragmented forests into smaller, less contiguous patches. In some parts of the country, intensive management and favorable climates have resulted in development of highly productive forests, such as southern pine plantations, in place of the natural land cover. Fire suppression, particularly in southeastern, midwestern, and western forests, has also led to changes in forest area and in species composition. Harvesting methods have also changed species composition, while planting trees for aesthetic and landscaping purposes in urban and rural areas has expanded the presence of some species. In addition, large areas, particularly in the Northeast, have become reforested as forests have taken over abandoned agricultural lands, allowing reestablishment of the ranges of many wildlife species.

Changes in climate and in the CO_2 concentration are emerging as important human-induced influences that are affecting forests. These factors are interacting with factors already causing changes in forests to further affect the socioeconomic benefits and the goods and services forests provide, including the extent, composition, and productivity of forests; the frequency and intensity of such natural disturbances as fire; and the level of biodiversity (NFAG 2001). Based on model projections of moderate to large warming, Figure 6-8 gives an example of the general character of changes that could occur for forests in the eastern United States by the late 21st century.

Effects on Forest Productivity

A synthesis of laboratory and field studies and modeling indicates that the fertilizing effect of atmospheric CO_2 will increase forest productivity. However, increases are likely to be strongly tempered by local conditions, such as moisture stress and nutrient availability. Across a wide range of scenarios, modest warming is likely to result in increased carbon storage in most U.S. forests, although under some of the warmer model scenarios, forests in the Southeast and the Northwest could experience drought-induced losses of carbon, possibly exacerbated by increased fire disturbance. These potential gains and losses of carbon would be in addition to changes resulting from changes in land use, such as the conversion of forests to agricultural lands or development.

Other components of environmental change, such as nitrogen deposition and ground-level ozone concentrations, are also affecting forest processes. Models used in the forest sector assessment suggest a synergistic fertilization response between CO_2 and nitrogen enrichment, leading to further increases in productivity (NFAG 2001). However, ozone acts in the opposite direction. Current ozone levels, for example, have important effects on many herbaceous species and are estimated to decrease production in southern pine plantations by 5 percent, in northeastern forests by 10 percent, and in some western forests by even more. Interactions among these physical and chemical changes and other components of global change will be important in projecting the future state of U.S. forests. For example, a higher CO_2 concentration can tend to suppress the impacts of ozone on plants.

Effects on Natural Disturbances

Natural disturbances having the greatest effects on forests include insects, disease, non-native species, fires, droughts, hurricanes, landslides, wind storms, and ice storms. While some tree species are very susceptible to fire, others, such as lodgepole pine, are dependent on occasional fires for successful reproduction.

Over millennia, local, regional, and global-scale changes in temperature and precipitation have influenced the occurrence, frequency, and intensity of these natural disturbances. These changes in disturbance regimes are a natural part of all ecosystems. However, as a consequence of climate change, forests may soon be facing more rapid alterations in the nature of these disturbances. For example, unless there is a large increase in precipitation, the seasonal severity of fire hazard is projected to increase during the 21st century over much of the country, particularly in the Southeast and Alaska.

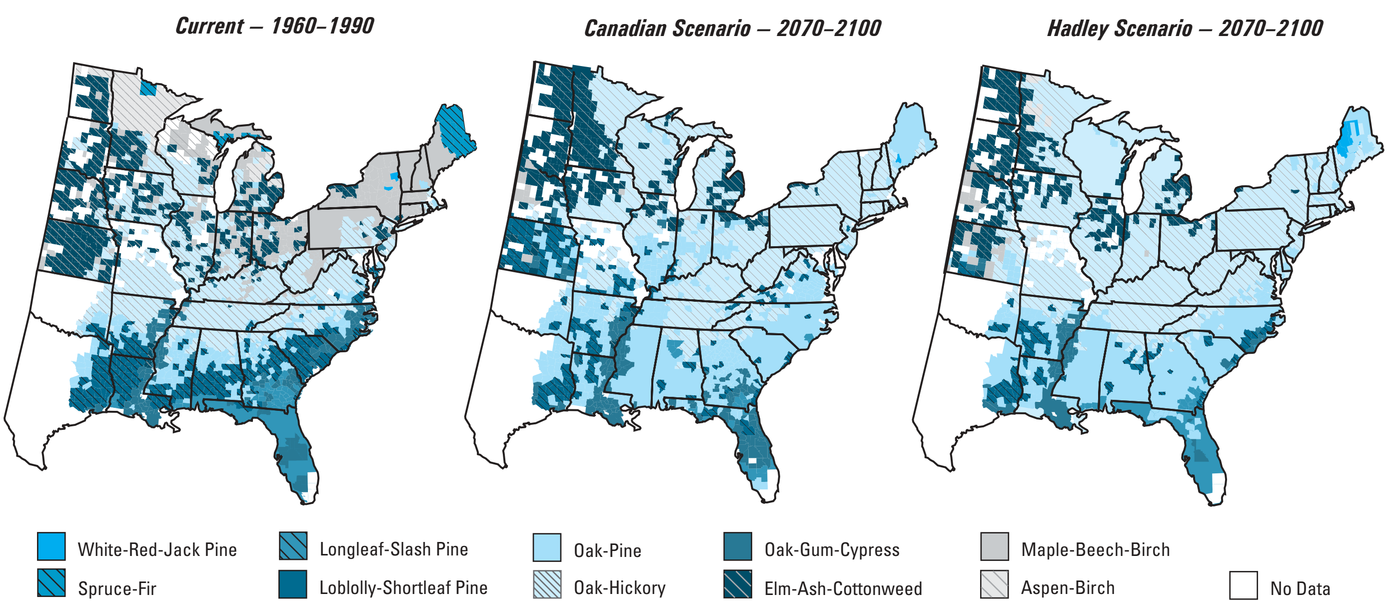
The consequences of drought depend on annual and seasonal climate changes and whether the current adaptations of forests to drought will offer resistance and resilience to new conditions. The ecological models used in the National Assessment indicated that increases in drought stresses are most likely to occur in the forests of the Southeast, southern Rocky Mountains, and parts of the Northwest. Hurricanes, ice storms, wind storms, landslides, insect infestations, disease, and introduced species are also likely to be climate-modulated influences that affect forests. However, projection of changes in the frequencies, intensities, and locations of such factors and their influences are difficult to project. What is clear is that, as climate changes, alterations in these disturbances and in their effects on forests are possible.

Effects on Forest Biodiversity

In addition to the very large influences of changes in land cover, changes in the distribution and abundance of plant and animal species are a result of both (1) the birth, growth, death, and dispersal rates of individuals in a population and (2) the competition between individuals of the same species and other species. These can all be influenced in

FIGURE 6-8 Potential Effects of Projected Climate Change on Dominant Forest Types

Both the warm-moist climate change scenario from the Hadley climate model and the hot-dry scenario from the Canadian climate model suggest a significant northward shift in prevailing forest types. For example, the maple-beech-birch forest type is projected to shift north into Canada and no longer be dominant in the late 21st century in the northeastern United States.



Note: All cases were calculated using the DISTRIB tree species distribution model, which calculates the most likely dominant types of vegetation for the given climatic conditions, assuming they have persisted for several decades.

Source: A.M. Prasad and L. R. Iverson, Northeastern Research Station, USDA Forest Service, Delaware, Ohio, as reported in NAST 2000.

turn by weather, climate, contaminants, nutrients, and other abiotic factors. When aggregated, these processes can result in the local disappearance or introduction of a species, and ultimately determine the species' range and influence its population.

Although climate and soils exert strong controls on the establishment and growth of plant species, the response of plant and animal species to climate change will be the result of many interacting and interrelated processes operating over several temporal and spatial scales. Movement and migration rates, changes in disturbance regimes and abiotic environmental variables, and interactions within and between species will all affect the distributions and populations of plants and animals.

Analyses conducted using ecological models indicate that plausible climate scenarios are very likely to cause shifts in the location and area of the potential habitats for many tree species. For example, potential habitats for trees acclimated to cool environments are very likely to shift northward. Habitats of alpine and sub-alpine spruce-fir in the contiguous United States are likely to be reduced and, possibly in the long term, eliminated as their mountain habitats warm. The extents of aspen, eastern birch, and sugar maple are likely to contract dramatically in the United States and largely shift into Canada, with the shift in sugar maple causing loss of syrup production in northern New York and New England. In contrast, oak/hickory and oak/pine could expand in the East, and Ponderosa pine and arid woodland communities could expand in the West. How well these species track changes in their potential habitats will be strongly influenced by the viability of their mechanisms for dispersal to other locations and the disturbances to these alternative environments.

Because of the dominance of nonforest land uses along migration routes, the northward shift of some native species to new habitats is likely to be disrupted if the rate of climate change is too rapid. For example, conifer encroachment, grazing, invasive species, and urban expansion are currently displacing sagebrush and aspen communities. The effects of climate change on the rate and magnitude of disturbance (forest damage and destruction associated with fires, storms, droughts, and pest outbreaks) will be important factors in determining whether transitions from one forest type to another will be gradual or abrupt. If the rate and type of disturbances in New England do not increase, for example, a smooth transition from the present maple, beech, and birch tree species to oak and hickory may occur. Where the frequency or intensity of disturbances increases, however, transitions are very likely to occur more rapidly. As these changes occur, invasive (weedy) species that disperse rapidly are likely to find opportunities in newly forming ecological communities. As a result, the species composition of these communities will likely differ significantly in some areas from those occupying similar habitats today.

Changes in the composition of ecosystems may, in turn, have important effects on wildlife. For example, to the extent that climate change and a higher CO_2 concentration increase forest productivity, this might result in reduced overall land disturbance and improved water quality, tending to help wildlife, at least in some areas. However, changes in composition can also affect predator–prey relationships, pest types and populations, the potential for non-native species, links in the chain of migratory habitats, the health of keystone species, and other factors. Given these many possibilities, much remains to be examined in projecting influences of climate change on wildlife.

Socioeconomic Impacts

North America is the world's leading producer and consumer of wood products. U.S. forests provide for substantial exports of hardwood lumber, wood chips, logs, and some types of paper. Coming the other way, the United States imports, for example, about 35 percent of its softwood lumber and more than half of its newsprint from Canada.

The U.S. market for wood products will be highly dependent upon the future area in forests, the species composition of forests, future supplies of wood, technological changes in production and use, the availability of such substitutes as steel and vinyl, national and international demands for wood products, and competitiveness among major trading partners. Analyses indicate that, for a range of climate scenarios, forest productivity gains are very likely to increase timber inventories over the next 100 years (NFAG 2001). Under these scenarios, the increased wood supply leads to reductions in log prices, helping consumers, but decreasing producers' profits. The projected net effect on the economic welfare of participants in timber markets increases by about 1 percent above current values.

Analyses conducted for the forest sector assessment indicate that land use will likely shift between forestry and agriculture as these economic sectors adjust to climate-induced changes in production. U.S. hardwood and softwood production is projected to generally increase, although the projections indicate that softwood output will only increase under moderate warming. Timber output is also projected to increase more in the South than in the North, and saw-timber volume is projected to increase more than pulpwood volume.

Patterns and seasons of outdoor, forest-oriented recreation are likely to be modified by the projected changes in climate. For example, changes in forest-oriented recreation, as measured by aggregate days of activities and total economic value, are likely to be affected and are likely to vary by type of recreation and location. In some areas, higher temperatures are likely to shift typical summer recreation activities, such as hiking, northward or to higher elevations and into other seasons. In winter, downhill skiing opportunities are very likely to shift geographically because of fewer cold days and reduced snowpack in many existing ski areas. Therefore, costs to maintain skiing opportunities are likely to rise, especially for the more southern areas. Effects on fishing are also likely to vary. For example, warmer waters are likely to increase fish production and opportunities to fish for some warm-water species, but decrease habitat and opportunities to fish for cold-water species.

Possible Adaptation Strategies to Protect Forests

Even though forests are likely to be affected by the projected changes in climate, the motivation for adaptation strategies is likely to be most strongly influenced by the level of U.S. economic activity. This level, in turn, is intertwined with the rate of population growth, changes in taste, and general preferences, including society's perceptions about these changes. Market forces have proven to be powerful when it comes to decisions involving land use and forestry and, as such, will strongly influence adaptation on private lands. For forests valued for their current biodiversity, society and land managers will have to decide whether more intense management is necessary and appropriate for maintaining plant and animal species that may be affected by climate change and other factors.

If new technologies and markets are recognized in a timely manner, timber producers could adjust and adapt to climate change under plausible climate scenarios. One possible adaptation measure could be to salvage dead and dying timber and to replant species adapted to the changed climate conditions. The extent and pattern of U.S. timber harvesting and prices will also be influenced by the global changes in forest productivity and prices of overseas products.

Potential climate-induced changes in forests must also be put into the context of other human-induced pressures, which will undoubtedly change significantly over future decades. While the potential for rapid changes in natural disturbances could challenge current management strategies, these changes will occur simultaneously with human activities, such as agricultural and urban encroachment on forests, multiple uses of forests, and air pollution. Given these many interacting factors, climate-induced changes should be manageable if planning is proactive.

Potential Interactions with Water Resources

Water is a central resource supporting human activities and ecosystems, and adaptive management of this resource has been an essential aspect of societal development. Increases in global temperatures during the 20th century have been accompanied by more precipitation in the middle and high latitudes in many regions of North America. For example, U.S. precipitation increased by 5–10 percent, predominantly from the spring through the autumn. Much of this increase resulted from a rise in locally heavy and very heavy precipitation events, which has led to the observed increases in low to moderate stream flow that have been characteristic of the warm season across most of the contiguous United States.

Local to global aspects of the hydrologic cycle, which determine the availability of water resources, are likely to be altered in important ways by climate change (NWAG 2000). Because higher concentrations of CO_2 and other greenhouse gases tend to warm the surface, all models project that the global totals of both evaporation and precipitation will continue to increase, with increases particularly likely in middle and high latitudes.

The regional patterns of the projected changes in precipitation remain uncertain, however, although there are some indications that changes in atmospheric circulation brought on by such factors as increasing Pacific Ocean temperatures may bring more precipitation to the Southwest and more winter precipitation to the West. Continuing trends first evident during the 20th century, model simulations project that increases in precipitation are likely to be most evident in the most intense rainfall categories typical of various regions. To the extent such increases occur during the warm season when stream flows are typically low to moderate, they could augment available water resources. If increases in precipitation occur during high stream flow or saturated soil conditions, the results suggest a greater potential for flooding in susceptible areas where additional control measures are not taken, especially because under these conditions the relative increase in runoff is generally observed to be greater than the relative increase in precipitation.

Effects on Available Water Supplies

Water is a critical national resource, providing services to society for refreshment, irrigation of crops, nourishment of ecosystems, creation of hydroelectric power, industrial processing, and more. Many U.S. rivers and streams do not have enough water to satisfy existing water rights and claims. Changing public values about preserving in-stream flows, protecting endangered species, and settling Indian water rights claims have made competition for water supplies increasingly intense. Depending on how water managers are able to take adaptive measures, the potential impacts of climate change could include increased competition for water supplies, stresses on water quality in areas where flows are diminished, adverse impacts on ground-water quantity and quality, an increased possibility of flooding in the winter and early spring, a reduced possibility of flooding later in the spring, and more water shortages in the summer. In some areas, however, an increase in precipitation could outweigh these factors and increase available supplies.

Significant changes in average temperature, precipitation, and soil moisture resulting from climate change are also likely to affect water demand in most sectors. For example, demand for water associated with electric power generation is projected to increase due to the increasing demand for air conditioning with higher summer temperatures.

Climate change is also likely to reduce water levels in the Great Lakes and summertime river levels in the central United States, thereby adversely affecting navigation, general water supplies, and populations of aquatic species.

Effects on Water Quality

Increases in heavy precipitation events are likely to flush more contaminants and sediments into lakes and rivers, degrading water quality. Where uptake of agricultural chemicals and other nonpoint sources could be exacerbated, steps to limit water pollution are likely to be needed. In some regions, however, higher average flows will likely dilute pollutants and, thus, improve water quality. In coastal regions where river flows are reduced, increased salinity could also become more of a problem. Flooding can also cause overloading of storm-water and wastewater systems, and can damage water and sewage treatment facilities, mine tailing impoundments, and landfills, thereby increasing the risks of contamination and toxicity.

Because the warmer temperatures will lead to increased evaporation, soil moisture is likely to be reduced during the warm season. Although this effect is likely be alleviated somewhat by increased efficiency in water use and reduced demand by native plants for water, the drying is likely to create a greater susceptibility to fire and then loss of the vegetation that helps to control erosion and sediment flows. In agricultural areas, the CO_2-induced improvement of water-use efficiency by crops is likely to decrease demands for water, particularly for irrigation water. In addition, in some regions, increasing no-till or reduced-till agriculture is likely to improve the water-holding capacity of soils, regardless of whether climate changes, thereby reducing the susceptibility of agricultural lands to erosion from intensified heavy rains (NAAG 2002, NWAG 2000).

Effects on Snowpack

Rising temperatures are very likely to affect snowfall and increase snowmelt conditions in much of the western and northern portions of the country that depend on winter snowpack for runoff. This is particularly important because snowpack provides a natural reservoir for water storage in mountainous areas, gradually releasing its water in spring and even summer under current climate conditions.

Model simulations project that snowpack in western mountain regions is likely to decrease as U.S. climate warms (Figure 6-9). These reductions are projected, despite an overall increase in precipitation, because (1) a larger fraction of precipitation will fall as rain, rather than snow; and (2) the snowpack is likely to develop later and melt earlier. The resulting changes in the amount and timing of runoff are very likely to have significant implications in some basins for water management, flood protection, power production, water quality, and the availability of water resources for irrigation, hydropower, communities, industry, and the sustainability of natural habitats and species.

Effects on Ground-Water Quantity and Quality

Several U.S. regions, including parts of California and the Great Plains, are dependent on dwindling ground-water supplies. Although ground-water supplies are less susceptible to short-term climate variability than surface-water supplies, they are more affected by long-term trends. Ground water serves as the base flow for many streams and rivers. Especially in areas where springtime snow cover is reduced and where higher summer temperatures increase evaporation and use of ground water for irrigation, ground-water levels are very likely to fall, thus reducing seasonal stream flows. River and stream temperatures fluctuate more rapidly with reduced volumes of water, affecting fresh-water and estuarine habitats. Small streams that are heavily influenced by ground water are more likely to have reduced flows and changes in seasonality of flows, which in turn is likely to damage existing wetland habitats.

Pumping ground water at a faster rate than it can be recharged is already a major concern, especially in parts of the country where other water resources are limited. In the Great Plains, for example, model projections indicate that drought is likely to be more frequent and intense, which will create additional stresses because ground-water levels are already dropping in parts of important aquifers, such as the Ogallala.

The quality of ground water is being diminished by a variety of factors, including chemical contamination. Salt-water intrusion is another key ground-water quality concern, particularly in coastal areas where changes in fresh-water flows and increases in sea level will both occur. As ground-water pumping increases to serve municipal demand along the coast and less recharge occurs, coastal ground-water aquifers are increasingly being affected by sea-water intrusion. Because the ground-water resource has been compromised by many factors, managers are increasingly looking to surface-water supplies, which are more sensitive to climate change and variability.

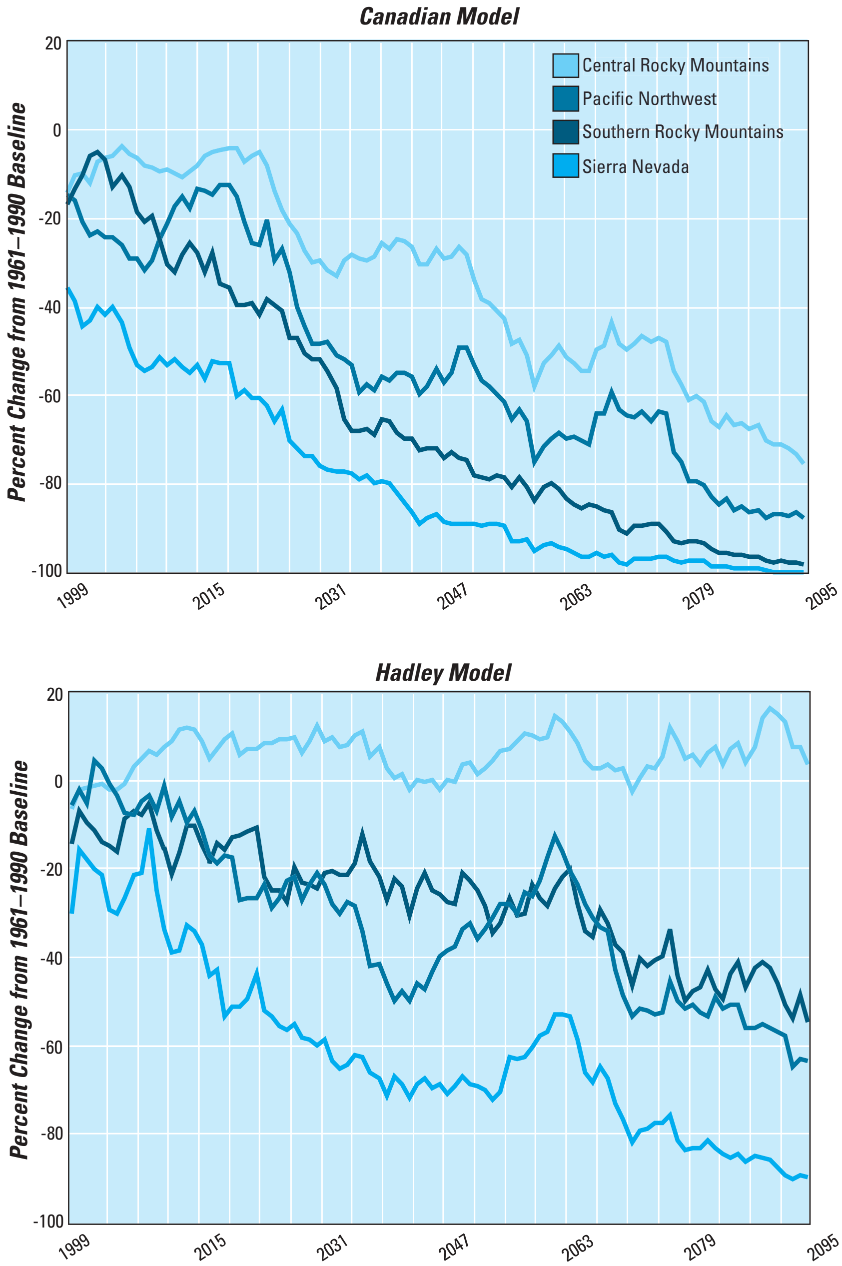
Effects on Floods, Droughts, and Heavy Precipitation Events

Projected changes in the amount, timing, and distribution of rainfall and snowfall are likely to lead to changes in the amount and timing of high and low water flows—although the relationships of changes in precipitation rate to changes in flood frequency and intensity are uncertain, especially due to uncertainties in the timing and persistence of rainfall events and river levels and capacities. Because changes in climate extremes are more likely than changes in climate averages to affect the magnitude of damages and raise the need for adaptive measures at the regional level, changes in the timing of precipitation events, as well as increases in the intensity of precipitation events, are likely to become increasingly important considerations.

Climate change is likely to affect the frequency and amplitude of high stream flows, with major implications for

FIGURE 6-9 Projected Reductions in Western Snowpack Resulting from Potential Changes in Climate

Climate model scenarios for the 21st century project significant decreases from the 1961–1990 baseline in the average April 1 snowpack for four mountainous areas in the western United States. Scenarios from the Canadian model, which simulates warming toward the upper end of IPCC projections, and from the Hadley model, which simulates warming near the middle of IPCC projections, provide similar results. Such a steep reduction in the April 1 snowpack would significantly shift the time of peak runoff and reduce average river flows in spring and summer.



Source: Redrawn from McCabe and Wolock 1999, as presented in NAST 2000.

infrastructure and emergency management in areas vulnerable to flooding. Although projections of the number of hurricanes that may develop remain uncertain, model simulations indicate that, in a warmer climate, hurricanes that do develop are likely to have higher wind speeds and produce more rainfall. As a result, they are likely to cause more damage, unless more extensive (and therefore more costly) adaptive measures are taken, including reducing the increasing exposure of property to such extreme events. Historical records indicate that improved warning has been a major factor in reducing the annual number of deaths due to storms, and that the primary cause of the increasing property damage in recent decades has been the increase in at-risk structures, such as widespread construction of vacation homes on barrier islands.

Despite the overall increase in precipitation and past trends indicating an increase in low to moderate stream flow, model simulations suggest that increased air temperatures and more intense evaporation are likely to cause many interior portions of the country to experience more frequent and longer dry conditions. To the extent that the frequency and intensity of these conditions lead to an increase in droughts, some areas are likely to experience wide-ranging impacts on agriculture, water-based transportation, and ecosystems, although the effects on vegetation (including crops and forests) are likely to be mitigated under some conditions by increased efficiency in water use due to higher CO_2 levels.

Water-driven Effects on Ecosystems

Species live in the larger context of ecosystems and have differing environmental needs. In some ecosystems, existing stresses could be reduced if increases in soil moisture or the incidence of freezing conditions are reduced. Other ecosystems, including some for which extreme conditions are critical, are likely to be most affected by changes in the frequency and intensity of flood, drought, or fire events. For example, model projections indicate that changes in temperature, moisture availability, and the water demand from vegetation are likely to lead to significant changes in some ecosystems in the coming decades (NAST 2000). As specific examples, the natural ecosystems of the Arctic, Great Lakes, Great Basin, and Southeast, and the prairie potholes of the Great Plains appear highly vulnerable to the projected changes in climate (see Figures 6-6 and 6-8).

The effects of changes in water temperatures are also important. For example, rising water temperatures are likely to force out some cold-water fish species (such as salmon and trout) that are already near the threshold of their viable habitat, while opening up additional areas for warm-water species. Increasing temperatures are also likely to decrease dissolved oxygen in water, degrade the health of ecosystems, reduce ice cover, and alter the mixing and stratification of water in lakes—all of which are key to maintaining optimal habitat and suitable nutrient levels. In addition, warmer lake waters combining with excess nutrients from agricultural fertilizers (washed into lakes by heavy rains) would be likely to create algal blooms on the lake surfaces, further depleting some lake ecosystems of life-sustaining oxygen.

Potential Adaptation Options to Ensure Adequate Water Resources

In contrast to the vulnerability of natural ecosystems, humans have exhibited a significant ability to adapt to the availability of different amounts of water. There are many types of water basins across the country, and many approaches are already in use to ensure careful management of water resources. For example, more than 80,000 dams and reservoirs and millions of miles of canals, pipes, and tunnels have been developed to store and transport water. Some types of approaches that studies have indicated might prove useful are highlighted on this page.

Strategies for adapting to climate change and other stresses include changing the operation of dams and reservoirs, re-evaluating basic engineering assumptions used in facility construction, and building new infrastructure (although for a variety of reasons, large dams are no longer generally viewed as a cost-effective or environmentally acceptable solution to water supply problems). Other potentially available options include conserving water; changing water pricing; using reclaimed wastewater; using water transfers; and developing markets for water, which can lead to increased prices that discourage wasteful practices.

Existing or new infrastructure can also be used to dampen the impacts of climate-induced influences on flow regimes and aquatic ecosystems of many of our nation's rivers. While significant adaptation is possible, its cost could be reduced if the probable effects of climate change are factored in before making major long-term investments in repairing, maintaining, expanding, and operating existing water supply and management infrastructure.

Because of the uncertainties associated with the magnitude and direction of changes in precipitation and runoff due to climate change, more flexible institutional arrangements may be needed to ensure optimal availability of water as supplies and demand change. Although social, equity, and environmental considerations must be addressed, market solutions offer the potential for resolving supply problems in some parts of the country. However, because water rights systems vary from state to state and even locally, water managers will need to take the lead in selecting the most appropriate adaptive responses.

Because the United States shares water resources with Canada and Mexico, it participates in a number of institutions designed to address common water issues. These institutions, which include the U.S.–Canada Great Lakes Commission and joint commissions and agreements covering the Colorado and Rio Grande rivers, could provide the framework for designing adaptive measures for responding to the effects of climate change. For example, the U.S.–Canada Great Lakes Commission has already conducted studies to evaluate options for dealing with the potential for increased evaporation, shorter duration of lake ice, and other climate changes that are projected to affect the Great Lakes–St. Lawrence River basin.

Potential Adaptation Options for Water Management

Following are some potential adaptation options for water management in response to climate change and other stresses:

- Improve capacity for moving water within and between water-use sectors (including agriculture to urban).
- Use pricing and market mechanisms proactively to decrease waste.
- Incorporate potential changes in demand and supply in long-term planning and infrastructure design.
- Create incentives to move people and structures away from flood plains.
- Identify ways to sustainably manage supplies, including ground water, surface water, and effluent.
- Restore and maintain watersheds to reduce sediment loads and nutrients in runoff, limit flooding, and lower water temperature.
- Encourage the development of institutions to confer property rights to water. This would be intended to encourage conservation, recycling, and reuse of water by all users, as well as to provide incentives for research and development of such conservation technologies.
- Reduce agricultural demand for water by focusing research on development of crops and farming practices for minimizing water use, for example, via precision agricultural techniques that closely monitor soil moisture.
- Reuse municipal wastewater, improve management of urban storm-water runoff, and promote collection of rain water for local use.
- Increase the use of forecasting tools for water management. Some weather patterns, such as those resulting from El Niño, can now be predicted, allowing for more efficient management of water resources.
- Enhance monitoring efforts to improve data collection for weather, climate, and hydrologic modeling to aid understanding of water-related impacts and management strategies.

Source: Adapted from NWAG 2000.

Close coordination will be needed to efficiently manage the levels of these crucial water resources to ensure adequate water supplies for communities and irrigation, high water quality, needed hydroelectric power, high enough levels for recreation and shipping, low enough levels to protect communities and shorelines from flooding and wave-induced erosion, and more.

Potential Interactions with Coastal Areas and Marine Resources

The United States has over 95,000 miles of coastline and over 3.4 million square miles of ocean within its territorial waters. These areas provide a wide range of goods and services to the U.S. economy. Approximately 53 percent of the U.S. population lives on the 17 percent of land in counties that are adjacent to or relatively near the coast. Over recent decades, populations in these coastal counties have been growing more rapidly than elsewhere in the country. As a result of this population growth and increased wealth, demands on coastal and marine resources for both leisure activities and economic benefits are rapidly intensifying, while at the same time exposure to coastal hazards is increasing.

Coastal and marine environments are intrinsically linked to the prevailing climate in many ways. Heat given off by the oceans warms the land during the winter, and ocean waters help to keep coastal regions cooler during the summer. Moisture evaporated from the oceans is the ultimate source of precipitation, and the runoff of precipitation carries nutrients, pollutants, and other materials from the land to the ocean. Sea level exerts a major influence on the coastal zone, shaping barrier islands and pushing salt water up estuaries and into aquifers. For example, cycles of beach and cliff erosion along the Pacific Coast have been linked to the natural sequence of El Niño events that alter storm tracks and temporarily raise average sea levels by several inches in this region (NCAG 2000). During the 1982–83 and 1997–98 El Niño events, erosion damage was widespread along the Pacific coastline.

Climate change will affect interactions among conditions on the land and sea and in the atmosphere. Warming is likely to alter coastal weather and could affect the intensity, frequency, and extent of severe storms. Melting of glaciers and ice sheets and thermal expansion of ocean waters will cause sea level to rise, which is likely to intensify erosion and endanger coastal structures. Rising sea level and higher temperatures are also likely to affect the ecology of estuaries and coastal wetlands. Higher temperatures coupled with increasing CO_2 concentrations are likely to severely stress coral reefs, and the changing temperature patterns are likely to cause fisheries to relocate and alter fish migration patterns. While quantifying these consequences is difficult, indications of the types of outcomes that are possible have emerged from U.S. assessments (NCAG 2000).

Effects on Sea Level

Global sea level rose by 10–20 cm (about 4–8 inches) during the 20th century, which was significantly more than the rate of rise that was typical over the last few thousand years. Even in the absence of a change in Atlantic storminess, the deeper inundation that has resulted from recent storms has exacerbated flooding and has led to damage to fixed coastal structures from storms that were previously inconsequential.

Looking to the future, climate models project that global warming will increase sea level by 9–88 cm (4–35 inches) during the 21st century, with mid-range values more likely than the very high or very low estimates (IPCC 2001d). Because of the long time constants involved in ocean warming and glacier and ice sheet melting, further sea level rise is likely for several centuries, even after achieving significant limitations in emissions of CO_2 and other greenhouse gases. However, these global changes are only one factor in what determines sea level change at any particular coastal location. For example, along the Mid-Atlantic coast, where land levels are subsiding, relative sea level rise will be somewhat greater; conversely, in New England, where land levels are rising, relative sea level rise will be somewhat less.

Not surprisingly, an increased rate of global sea level rise is likely to have the most dramatic impacts in regions where subsidence and erosion problems already exist. Estuaries, wetlands, and shorelines along the Atlantic and Gulf coasts are especially vulnerable. Impacts on fixed structures will intensify, even in the absence of an increase in storminess. However, because the slope of these areas is so gentle, even a small rise in sea level can produce a large inland shift of the shoreline. The rise will be particularly important if the frequency or intensity of storm surges or hurricanes increases.

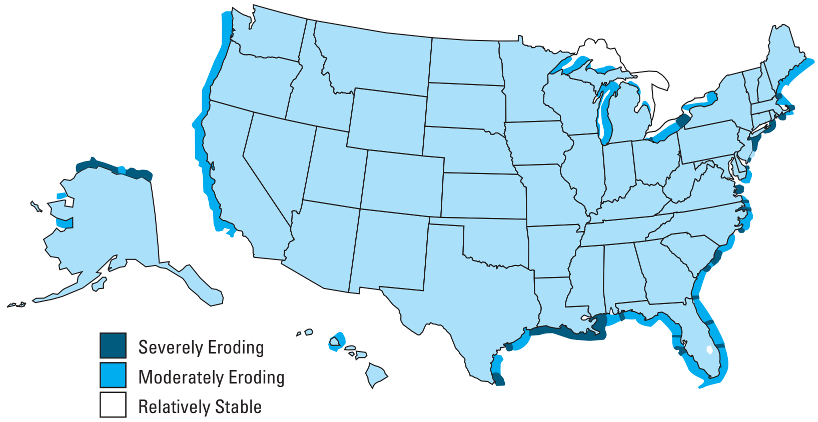
Increases in the frequency or intensity of El Niño events would also likely exacerbate the impacts of long-term sea level rise. Coastal erosion increases the threats to coastal development, transportation infrastructure, tourism, freshwater aquifers, fisheries (many of which are already stressed by human activities), and coastal ecosystems. Coastal cities and towns, especially those in storm-prone regions, such as the Southeast, are particularly vulnerable. Intensive residential and commercial development in these regions is placing more and more lives and property at risk (Figure 6-10).

Effects on Estuaries

Climate change and sea level rise could present significant threats to valuable, productive coastal ecosystems. For example, estuaries filter and purify water and provide critical nursery and habitat functions for many commercially important fish and shellfish populations. Because the temperature increase is projected to be greater in the winter than in the summer, a narrowing of the annual water temperature range of many estuaries is likely. This, in turn, is likely to cause a shift in species' ranges and to increase the vulnerability of some estuar-

FIGURE 6-10 **Projected Rates of Annual Erosion along U.S. Shorelines**

The U.S. coastal areas that are most vulnerable to future increases in sea level are those with low relief and those that are already experiencing rapid erosion rates, such as the Southeast and Gulf Coast.



Source: U.S. Geological Survey Coastal Geology Program, as presented in NAST 2000.

ies to invasive species (NCAG 2000).

Changes in runoff are also likely to adversely affect estuaries. Unless new agricultural technologies allow reduced use of fertilizers, higher rates of runoff are likely to deliver greater amounts of nutrients such as nitrogen and phosphorus to estuaries, while simultaneously increasing the stratification between fresh-water runoff and marine waters. Such conditions would be likely to increase the potential for algal blooms that deplete the water of oxygen. These conditions would also increase stresses on sea grasses, fish, shellfish, and other organisms living in lakes, streams, and oceans (NCAG 2000, and regional assessment reports listed at http://www.usgcrp.gov). In addition, decreased runoff is likely to reduce flushing, decrease the size of estuarine nursery zones, and increase the range of estuarine habitat susceptible to predators and pathogens of shellfish.

Effects on Wetlands

Coastal wetlands (marshes and mangroves) are highly productive ecosystems, particularly because they are strongly linked to the productivity of fisheries. Dramatic losses of coastal wetlands have occurred along the Gulf Coast due to subsidence, alterations in flow and sediment load caused by dams and levees, dredge and fill activities, and sea level rise. Louisiana alone has been losing land at rates of about 68–104 square kilometers (24–40 square miles) per year for the last 40 years, accounting for as much as 80 percent of the total U.S. coastal wetland loss.

In general, coastal wetlands will survive if soil buildup equals the rate of relative sea level rise or if they are able to migrate inland (although this migration necessarily displaces other ecosystems or land uses). However, if soil accumulation does not keep pace with sea level rise, or if bluffs, coastal development, or shoreline protective structures (such as dikes, sea walls, and jetties) block wetland migration, wetlands may be excessively inundated and, thus, lost. The projected increase in the current rate of sea level rise is very likely to exacerbate the nationwide rate of loss of existing coastal wetlands, although the extent of impacts will vary among regions, and some impacts may be moderated by the inland formation of new wetlands.

Effects on Coral Reefs

The demise or continued deterioration of reefs could have profound implications for the United States. Coral reefs play a major role in the environment and economies of Florida and Hawaii as well as in most U.S. territories in the Caribbean and Pacific. They support fisheries, recreation, and tourism and protect coastal areas. In addition, coral reefs are one of the largest global storehouses of marine biodiversity, sheltering one-quarter of all marine life and containing extensive untapped genetic resources.

The last few years have seen unprecedented declines in the health of coral reefs. The 1998 El Niño was associated with record sea-surface temperatures and associated coral bleaching (which occurs when coral expel the algae that live within them and that are necessary to their survival). In some regions, as much as 70 percent of the coral may have died in a single season. There has also been an upsurge in the variety, incidence, and virulence of coral diseases in recent years, with major die-offs in Florida and much of the Caribbean region (NCAG 2000).

Other factors that are likely to be contributing to the decline of coral reefs include increased sediment deposition, sewage and agricultural runoff, excessive harvesting of fish, and damage from ships and tourists. In addition to the potential influences of further global warming, increasing atmospheric CO_2 concentrations are likely to decrease the calcification rates of the reef-building corals, resulting in weaker skeletons, reduced growth rates, and increased vulnerability to wave-induced damage. Model results suggest that these effects would likely be most severe at the current margins of coral reef distribution, meaning that it is unlikely coral reefs will be able to spread northward to reach cooler waters. While steps can be taken to reduce the impacts of some types of stress on coral reefs (e.g., by creating Marine Protected Areas, as called for in Executive Order 13158, and constructing artificial reefs to provide habitat for threatened species), damage to coral reefs from climate change and the increasing CO_2 concentration may be moderated to some extent only by significantly reducing other stresses.

Effects on Marine Fisheries

Based on studies summarized in the coastal sector assessment, recreational and commercial fishing has contributed approximately $40 billion a year to the U.S. economy, with total marine landings averaging about 4.5 million metric tons over the last decade. Climate change is very likely to substantially alter the distribution and abundance of major fish stocks, many of which are a shared international resource.

Along the Pacific Coast, impacts to fisheries related to the El Niño–Southern Oscillation illustrate how climate directly affects marine fisheries on short time scales. For example, elevated sea-surface temperatures associated with the 1997–98 El Niño had a tremendous impact on the distribution and abundance of market squid. Although California's largest fishery by volume, squid landings fell to less than 1,000 metric tons in the 1997–98 season, down from a record-breaking 110,000 metric tons in the 1996–97 season. Many other unusual events occurred during this same El Niño as a result of elevated sea-surface temperatures. Examples include widespread deaths of California sea lion pups, catches of warm-water marlin in the usually frigid waters off Washington State, and poor salmon returns in Bristol Bay, Alaska.

The changes in fish stocks resulting from climate change are also likely to have important implications for marine populations and ecosystems. Changes over the long term that will affect all nations are likely to include poleward shifts in distribution of marine populations, and changes in the timing, locations, and, perhaps, viability of migration paths and nesting and feeding areas for marine mammals and other species.

With changing ocean temperatures and conditions, shifts in the distribution of commercially important species are likely, affecting U.S. and international fisheries. For example, model projections suggest that several species of Pacific salmon are likely to have reduced distribution and productivity, while species that thrive in warmer waters, such as Pacific sardine and Atlantic menhaden, are likely to show an increased distribution. Presuming that the rate of climate change is gradual, the many efforts being made to better manage the world's fisheries might promote adaptation to climate change, along with helping to relieve the many other pressures on these resources.

Potential Adaptation Options for Coastal Regions

Because climate variability is currently a dominant factor in shaping coastal and marine systems, projecting the specific effects of climate change over the next few decades and evaluating the potential effectiveness of possible response options is particularly challenging. Effects will surely vary greatly among the diverse coastal regions of the nation. Human-induced disturbances also influence coastal and marine systems, often reducing the ability of systems to adapt, so that systems that might ordinarily be capable of responding to variability and change are less able to do so. In this context, climate change is likely to add to the cumulative impact of both natural and human-caused stresses on ecological systems and resources. As a result, strategies for adapting to the potential consequences of long-term climate change in the overall context of coastal development and management are only beginning to be considered (NCAG 2000).

However, as further plans are made for development of land in the coastal zone, it is especially urgent for governing bodies at all levels to begin to consider the potential changes in the coastal climate and sea level. For example, the U.S. Geological Survey is expanding its gathering and assembly of relevant coastal information, and the U.S. Environmental Protection Agency's Sea Level Rise project is dedicated to motivating adaptation to rising sea level. This project has assessed the probability and has identified and mapped vulnerable low-elevation coastal zones. In addition, cost-effective strategies and land-use planning approaches involving landward migration of wetlands, levee building, incorporation of sea level rise in beach conservation plans, engineered landward retreats, and sea walls have all been developed.

Several states have already included sea level rise in their planning, and some have already implemented adaptation activities. For example, in New Jersey, where relative sea level is rising approximately one inch (2.5 cm) every six years, $15 million is now set aside each year for shore protection, and the state discourages construction that would later require sea walls. In addition, Maine, Rhode Island, South Carolina, and Massachusetts have implemented various forms of "rolling easement" policies to ensure that wetlands and beaches can migrate inland as sea level rises, and that coastal landowners and conservation agencies can purchase the required easements. Other states have modified regulations on, for example, beach preservation, land reclamation, and inward migration of wetlands and beaches. Wider consideration of potential consequences is especially important, however, because some regulatory programs continue to permit structures that may block the inland shift of wetlands and beaches, and in some locations shoreline movement is precluded due to the high degree of coastal development.

To safeguard people and better manage resources along the coast, NOAA provides weather forecasts and remotely sensed environmental data to federal, state, and local governments, coastal resource managers and scientists, and the public. As part of its mandate and responsibilities to administer the National Flood Insurance Program, the Federal Emergency Management Agency (FEMA) prepares Flood Insurance Rate Maps that identify and delineate areas subject to severe (1 percent annual chance) floods. FEMA also maps coastal flood hazard areas as a separate flood hazard category in recognition of the additional risk associated with wave action. In addition, FEMA is working with many coastal cities to encourage steps to reduce their vulnerability to storms and floods, including purchasing vulnerable properties.

University and state programs are also underway across the country. This is particularly important because most coastal planning in the United States is the responsibility of state and local governments, with the federal government interacting with these efforts through the development of coastal zone management plans.

Potential Interactions with Human Health

Although the overall susceptibility of Americans to environmental health concerns dropped dramatically during the 20th century, certain health outcomes are still recognized to be associated with the prevailing environmental conditions. These adverse outcomes include illnesses and deaths associated with temperature extremes; storms and other heavy precipitation events; air pollution; water contamination; and diseases carried by mosquitoes, ticks, and rodents. As a result of the potential consequences of these stresses acting individually or in combination, it is possible that projected climate change will have measurable beneficial and adverse impacts on health (see NHAG 2000, 2001).

Adaptation offers the potential to reduce the vulnerability of the U.S. population to adverse health outcomes—including possible outcomes of projected climate change—primarily by ensuring strong public health systems, improving their responsiveness to changing weather and climate conditions, and expanding attention given to vulnerable subpopulations. Although the costs, benefits, and availability of resources for such adaptation must be found, and further research into key knowledge gaps on the relationships between climate/weather and health is needed, to the extent that the U.S. population can keep from putting itself at greater risk by where it lives and what it does, the potential impacts of climate change on human health can likely be addressed as a component of efforts to address current vulnerabilities.

Projections of the extent and direction of potential impacts of climate variability and change on health are extremely difficult to make with confidence because of the many confounding and poorly understood factors associated with potential health outcomes. These factors include the sensitivity of human health to aspects of weather and climate, differing vulnerability of various demographic and geographic segments of the population, the international movement of disease vectors, and how effectively prospective problems can be dealt with. For example, uncertainties remain about how climate and associated environmental conditions may change. Even in the absence of improving medical care and treatment, while some positive health outcomes—notably, reduced cold-weather mortality—are possible, the balance between increased risk of heat-related illnesses and death and changes in winter illnesses and death cannot yet be confidently assessed. In addition to uncertainties about health outcomes, it is very difficult to anticipate what future adaptive measures (e.g., vaccines, improved use of weather forecasting to further reduce exposure to severe conditions) might be taken to reduce the risks of adverse health outcomes.

Effects on Temperature-Related Illnesses and Deaths

Episodes of extreme heat cause more deaths in the United States than any other category of deaths associated with extreme weather. In one of the most severe examples of such an event, the number of deaths rose by 85 percent during a five-day heat wave in 1995 in which maximum temperatures in Chicago, Illinois, ranged from 34 to 40°C (93 to 104°F) and minimum temperatures were nearly as high. At least 700 excess deaths (deaths in that population beyond those expected for that period) were recorded, most of which were directly attributable to heat.

For particular years, studies in certain urban areas show a strong association between increases in mortality and increases in heat, measured by maximum or minimum daily temperature and by heat index (a measure of temperature and humidity). Over longer periods, determination of trends is often difficult due to the episodic nature of such events and the presence of complicating health conditions, as well as because many areas are taking steps to reduce exposure to extreme heat. Recognizing these complications, no nationwide trend in deaths directly attributed to extreme heat is evident over the past two decades, even though some warming has occurred.

Based on available studies, heat stroke and other health effects associated with exposure to extreme and prolonged heat appear to be related to environmental temperatures above those to which the population is accustomed. Thus, the regions expected to be most sensitive to projected increases in severity and frequency of heat waves are likely to be those in which extremely high temperatures occur only irregularly. Within heat-sensitive regions, experience indicates that populations in urban areas are most vulnerable to adverse heat-related health outcomes. Daily average heat indices and heat-related mortality rates are higher in these urban core areas than in surrounding areas, because urban areas remain warmer throughout the night compared to outlying suburban and rural areas. The absence of nighttime relief from heat for urban residents has been identified as a factor in excessive heat-related deaths. The elderly, young children, the poor, and people who are bedridden, who are on certain medications, or who have certain underlying medical conditions are at particular risk.

Plausible climate scenarios project significant increases in average summer temperatures, leading to new record highs. Model results also indicate that the frequency and severity of heat waves would be very likely to increase along with the increase in average temperatures. The size of U.S. cities and the proportion of U.S. residents living in them are also projected to increase through the 21st century. Because cities tend to retain daytime heat and so are warmer than surrounding areas, climate change is very likely to lead to an increase in the population potentially at risk from heat events. While the potential risk may increase, heat-related illnesses and deaths are largely preventable through behavioral adaptations, including use of air conditioning, increased fluid intake, and community warning and support systems. The degree to which these adaptations can be even more broadly made available and adopted than in the 20th century, especially for sensitive populations, will determine if the long-term trend toward fewer deaths from extreme heat can be maintained.

Death rates not only vary with summertime temperature, but also show a seasonal dependence, with more deaths in winter than in summer. This relationship suggests that the relatively large increases in average winter temperature could reduce deaths in winter months. However, the relationship between winter weather and mortality is not as clear as for summertime extremes. While there should be fewer deaths from shoveling snow and slipping on ice, many winter deaths are due to respiratory infections, such as influenza, and it is not clear how influenza transmission would be affected by higher winter temperatures. As a result, the net effect on winter mortality from milder winters remains uncertain.

Influences on Health Effects Related to Extreme Weather Events

Injury and death also result from natural disasters, such as floods and hurricanes. Such outcomes can result both from direct bodily harm and from secondary influences, such as those mediated by changes in ecological systems (such as bacterial and fungal proliferation) and in public health infrastructures (such as reduced availability of safe drinking water).

Projections of climate change for the 21st century suggest a continuation of the 20th-century trend toward increasing intensity of heavy precipitation events, including precipitation during hurricanes. Such events, in addition to the potential consequences listed above, pose an increased risk of floods and associated health impacts. However, much can be done to prepare for powerful storms and heavy precipitation events, both through community design and through warning systems. As a result of such efforts, the loss of life and the relative amounts of damage have been decreasing. For the future, therefore, the net health impacts of extreme weather events hinge on continuing efforts to reduce societal vulnerabilities. For example, FEMA's Safe Communities program is promoting implementation of stronger building codes and improved warning systems, as well as enhancing the recovery capacities of the natural environment and the local population, which are also being addressed through disaster assistance programs.

Influences on Health Effects Related to Air Pollution

Current exposures to air pollution exceed health-based standards in many parts of the country. Health assessments indicate that ground-level ozone can exacerbate respiratory diseases and cause short-term reductions in lung function. Such studies also indicate that exposure to particulate matter can aggravate existing respiratory and cardiovascular diseases, alter the body's defense systems against foreign materials, damage lung tissue, lead to premature death, and possibly contribute to cancer. Health effects of exposure to carbon monoxide, sulfur dioxide, and nitrogen dioxide have also been related to reduced work capacity, aggravation of existing cardiovascular diseases, effects on breathing, respiratory illnesses, lung irritation, and alterations in the lung's defense systems.

Projected changes in climate would be likely to affect air quality in several ways, some of which are likely to be dealt with by ongoing changes in technology, and some of which can be dealt with, if necessary, through changes in regulations. For example, changes in the weather that affect regional pollution emissions and concentrations can be dealt with by controlling sources of emissions. However, adaptation will be needed in response to changes in natural sources of air pollution that result from changes in weather. Analyses show that hotter, sunnier days tend to increase the formation of ground-level ozone, other conditions being the same. This creates a risk of higher concentrations of ground-level ozone in the future, especially because higher temperatures are frequently accompanied by stagnating circulation patterns. However, more specific projections of exposure to air pollutants cannot be made with confidence without more accurate projections of changes in local and regional weather and projections of the amounts and locations of future emissions, which will in turn be affected by the implementation and success of air pollution control policies designed to ensure air quality. Also, more extensive health-warning systems could help to reduce exposures, decreasing any potential adverse consequences.

In addition to affecting exposure to air pollutants, there is some chance that climate change will play a role in exposure to airborne allergens. For example, it is possible that climate change will alter pollen production in some plants and change the geographic distribution of plant species. Consequently, there is some chance that climate change will affect the timing or duration of seasonal allergies. The impact of pollen and of pollen changes on the occurrence and severity of asthma, the most common chronic disease among children, is currently very uncertain.

Effects on Water- and Food-borne Diseases

In the United States, the incidence of and deaths due to waterborne diseases declined dramatically during the 20th century. While much less frequent or lethal nowadays, exposure to waterborne disease can still result from drinking contaminated water, eating seafood from contaminated water, eating fresh produce irrigated or processed with contaminated water, and participating in such activities as fishing or swimming in contaminated water. Water-borne pathogens of current concern include viruses, bacteria (such as *Vibrio vulnificus*, a naturally occurring estuarine bacterium responsible for a high percentage of the deaths associated with shellfish consumption), and protozoa (such as *Cryptosporidium*, associated with gastrointestinal illnesses).

Because changes in precipitation, temperature, humidity, salinity, and wind have a measurable effect on water quality, future changes in climate have the potential to increase exposure to water-borne pathogens. In 1993, for example, *Cryptosporidium* contaminated the Milwaukee, Wisconsin, drinking-water supply. As a result, 400,000 people became ill. Of the 54 individuals who died, most had compromised immune systems because of HIV infection or other illness. A contributing factor in the contamination, in addition to treatment system malfunctions, was heavy rainfall and runoff that resulted in a decline in the quality of raw surface water arriving at the Milwaukee drinking-water plants.

In another example, during the strong El Niño winter of 1997–98, heavy precipitation and runoff greatly elevated the counts of fecal bacteria and infectious viruses in Florida's coastal waters. In addition, toxic red tides proliferate as sea-water temperatures increase. Reports of marine-related illnesses have risen over the past two and a half decades along the East Coast, in correlation with El Niño events. Therefore, climate changes projected to occur in the next several decades—in particular, the likely increase in heavy precipitation events—raise the risk of contamination events.

Effects on Insect-, Tick-, and Rodent-borne Diseases

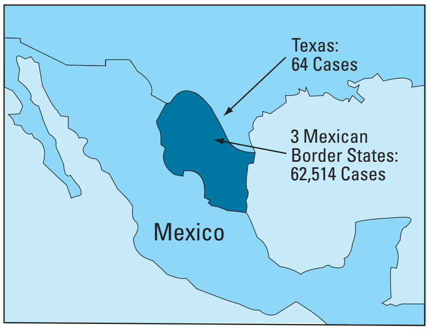
Malaria, yellow fever, dengue fever, and other diseases transmitted between humans by blood-feeding insects, ticks, and mites were once common in the United States. The incidence of many of these diseases has been significantly reduced, mainly because of changes in land use, agricultural methods, residential patterns, human behavior, vector control, and public health systems. However, diseases that may be transmitted to humans from wild animals continue to circulate in nature in many parts of the country. Humans may become infected with the pathogens that cause these diseases through transmission by insects or ticks (such as Lyme disease, which is tick-borne) or by direct contact with the host animals or their body fluids (such as hantaviruses, which are carried by numerous rodent species and transmitted to humans through contact with rodent urine, droppings, and saliva). The organisms that directly transmit these diseases are known as vectors.

The ecology and transmission dynamics of vector-borne infections are complex, and the factors that influence transmission are unique for each pathogen. Most vector-borne diseases exhibit a distinct seasonal pattern, which clearly suggests that they are weather-sensitive. Rainfall, temperature, and other weather variables affect both vectors and the pathogens they transmit in many ways. For example, epidemics of malaria are associated with rainy periods in some parts of the world, but with drought in others. Higher temperatures may increase or reduce vector survival rate, depending on each specific vector, its behavior, ecology, and many other factors. In some cases, specific weather patterns over several seasons appear to be associated with increased transmission rates. For example, in the Midwest, outbreaks of St. Louis encephalitis (a viral infection of birds that can also infect and cause disease in humans) appear to be associated with the sequence of warm, wet winters, cold springs, and hot, dry summers. Although the potential for such diseases seems likely to increase, both the U.S. National Assessment (NHAG 2000, 2001) and a special report prepared by the National Research Council (NRC 2001b) agree that significant outbreaks of these diseases as a result of climate change are unlikely because of U.S. health and community standards and systems. However, even with actions to limit breeding habitats of mosquitoes and other disease vectors and to carefully monitor for infectious diseases, the continued occurrence of local, isolated incidences of such diseases probably cannot be fully eliminated.

Although the United States has been able to reduce the incidence of such climatically related diseases as dengue and malaria, these diseases continue to extract a heavy toll elsewhere (Figure 6-11). Accordingly, the U.S. government and other governmental and nongovernmental organizations are actively supporting efforts to reduce the incidence and impacts of such diseases. For instance, U.S. agencies and philanthropies are in the forefront of malaria research, including the search for vaccines and genome sequencing of the anopheles mosquitoes and the malaria parasite *Plasmodium falciparum*. Efforts such as these should help to reduce global vulnerability to malaria and other vector-borne diseases, and need to be considered in global adaptation strategies.

FIGURE 6-11 Reported Cases of Dengue Fever: 1980–1999

In 1922, there were an estimated 500,000 cases of dengue fever in Texas. The mosquitoes that transmit this viral disease remain abundant. The striking contrast in incidence in Texas over the last two decades, and in three Mexican states that border Texas, illustrates the importance of factors other than climate in the incidence of vector-borne diseases.



Sources: National Institute of Health, Mexico, Texas Department of Health, U.S. Public Health Service, and unpublished data analyzed by the National Health Assessment Group and presented in NAST 2001.

The results from this work will serve the world in the event that human-induced climate change, through whatever mechanism, increases the potential for malaria. This work will also be beneficial for U.S. residents because our nation cannot be isolated from diseases occurring elsewhere in the world. Of significant importance, the potential for disease vectors to spread into the United States via travel and trade is likely to increase just as the natural, cold-winter conditions that have helped to protect U.S. residents are moderating.

Potential Adaptation Options to Ensure Public Health

The future vulnerability of the U.S. population to the health impacts of climate change will largely depend on maintaining—if not enhancing—the nation's capacity to adapt to potential adverse changes through legislative, administrative, institutional, technological, educational, and research-related measures. Examples include basic research into climate-sensitive diseases, building codes and zoning to prevent storm or flood damage, severe weather warning systems to allow evacuation, improved disease surveillance and prevention programs, improved sanitation systems, education of health professionals and the public, and research addressing key knowledge gaps in climate–health relationships.

Many of these adaptive responses are desirable from a public health perspective, irrespective of climate change. For example, reducing air pollution obviously has both short- and long-term health benefits. Improving warning systems for extreme weather events and eliminating existing combined sewer and storm-water drainage systems are other measures that can ameliorate some of the potential adverse impacts of current climate extremes and of the possible impacts of climate change. Improved disease surveillance, prevention systems, and other public health infrastructure at the state and local levels are already needed. Because of this, we expect awareness of the potential health consequences of climate change to allow adaptation to proceed in the normal course of social and economic development.

Potential Impacts in Various U.S. Regions

While some appreciation can be gained about the potential national consequences of climate change by looking at sectors such as the six considered above, the United States is a very large and diverse nation. There are both important commonalities and important differences in the climate-related issues and in the potential economic and environmental consequences faced by different regions across the country. Therefore, there are many different manifestations of a changing climate in terms of vulnerability and impacts, and the potential for adaptation. For example, while all coastal regions are at risk, the magnitude of the vulnerabilities and the types of adaptation necessary will depend on particular coastal conditions and development. Water is a key issue in virtually all regions, but the specific changes and impacts in the West, in the Great Lakes, and in the Southeast will differ.

With this variability in mind, 20 regional workshops that brought together researchers, stakeholders, and community, state, and national leaders were conducted to help identify key issues facing each region and to begin identifying potential adaptation strategies. These workshops were followed by the initiation of 16 regionally based assessment studies, some of which are already completed and others of which are nearing completion. Each of the regional studies has examined the potential consequences that would result from the climate model scenarios used in the national level analysis (the first finding in the Key National Findings on page 89), and from model simulations of how such climate changes would affect the types and distributions of ecosystems. The following page provides highlights of what has been learned about the regional mosaic of consequences from these studies. A much more comprehensive presentation of the results is included in the National Assessment regional reports (see http://www.usgcrp.gov).

In summarizing potential consequences for the United States, it is important to recognize that the U.S. government represents not only the 50 states, but also has trust responsibility for a number of Caribbean and Pacific islands and for the homelands of Native Americans. In particular, the U.S. government has responsibilities of various types for Puerto Rico, the American Virgin Islands, American Samoa, the Commonwealth of the Northern Mariana Islands, Guam, and more than 565 tribal and Alaska Native governments that are recognized as "domestic dependent nations."

For the island areas, the potential consequences are likely to be quite similar to those experienced by nearby U.S. states. With regard to Native Americans, treaties, executive orders, tribal legislation, acts of Congress, and decisions of the federal courts determine the relationships between the tribes and the federal government. These agreements cover a range of issues that will be important in facing the potential consequences of climate change, including use and maintenance of land and water resources. Although the diversity of land areas and tribal perspectives and situations makes generalizations difficult, a number of key issues have been identified for closer study concerning how climate variability and change will affect Native populations and their communities. These issues include tourism and community development; human health and extreme events; rights to and availability of water and other natural resources; subsistence economies and cultural resources; and cultural sites, wildlife, and natural resources. Closer examination of the potential consequences for tribes in the Southwest is the topic of one of the regional assessments now underway.

FEDERAL RESEARCH ACTIVITIES

The types and nature of impacts of climate change that are projected to

Key Regional Vulnerability and Consequence Issues

The following key vulnerability and consequence issues were identified across the set of regions considered in the U.S. National Assessment. Additional details may be found in the regional reports indexed at http://www.usgcrp.gov.

Northeast, Southeast, and Midwest—Rising temperatures are likely to increase the heat index dramatically in summer. Warmer winters are likely to reduce cold-related stresses. Both types of changes are likely to affect health and comfort.

Appalachians—Warmer and moister air is likely to lead to more intense rainfall events in mountainous areas, increasing the potential for flash floods.

Great Lakes—Lake levels are likely to decline due to increased warm-season evaporation, leading to reduced water supply and degraded water quality. Lower lake levels are also likely to increase shipping costs, although a longer shipping season is likely. Shoreline damage due to high water levels is likely to decrease, but reduced wintertime ice cover is likely to lead to higher waves and greater shoreline erosion.

Southeast—Under warmer, wetter scenarios, the range of southern tree species is likely to expand. Under hotter, drier scenarios, it is likely that grasslands and savannas will eventually displace southeastern forests in many areas, with the transformation likely accelerated by increased occurrence of large fires.

Southeast Atlantic Coast, Puerto Rico, and the Virgin Islands—Rising sea level and higher storm surges are likely to cause loss of many coastal ecosystems that now provide an important buffer for coastal development against the impacts of storms. Currently and newly exposed communities are more likely to suffer damage from the increasing intensity of storms.

Midwest/Great Plains—A rising CO_2 concentration is likely to offset the effects of rising temperatures on forests and agriculture for several decades, increasing productivity and thereby reducing commodity prices for the public. To the extent that overall production is not increased, higher crop and forest productivity is likely to lead to less land being farmed and logged, which may promote recovery of some natural environments.

Great Plains—Prairie potholes, which provide important habitat for ducks and other migratory waterfowl, are likely to become much drier in a warmer climate.

Southwest—With an increase in precipitation, the desert ecosystems native to this region are likely to be replaced in many areas by grasslands and shrublands, increasing both fire and agricultural potential.

Northern and Mountain Regions—It is very likely that warm-weather recreational opportunities like hiking will expand, while cold-weather activities like skiing will contract.

Mountain West—Higher winter temperatures are very likely to reduce late winter snowpack. This is likely to cause peak runoff to be lower, which is likely to reduce the potential for spring floods associated with snowmelt. As the peak flow shifts to earlier in the spring, summer runoff is likely to be reduced, which is likely to require modifications in water management to provide for flood control, power production, fish runs, cities, and irrigation.

Northwest—Increasing river and stream temperatures are very likely to further stress migrating fish, complicating current restoration efforts.

Alaska—Sharp winter and springtime temperature increases are very likely to cause continued melting of sea ice and thawing of permafrost, further disrupting ecosystems, infrastructure, and communities. A longer warm season could also increase opportunities for shipping, commerce, and tourism.

Hawaii and Pacific Trust Territories—More intense El Niño and La Niña events are possible and would be likely to create extreme fluctuations in water resources for island citizens and the tourists who sustain local economies.

affect the United States make clear that climate change is likely to become an increasingly important factor in the future management of our land and water resources. To better prepare for coming changes, it is important to enhance the basis of understanding through research and to start to consider the potential risks that may be created by these impacts in the making of short- and long-term decisions in such areas as planning for infrastructure, land use, and other natural resource management. To promote these steps, the U.S. government sponsors a wide range of related activities reaching across federal agencies and on to the states, communities, and the general public.

Interagency Research Subcommittees

At the federal level, climate change and, even more generally, global environmental change and sustainability are topics that have ties to many agencies across the U.S. government. To ensure coordination, the U.S. Congress passed the Global Change Research Act of 1990 (Public Law 101-606). This law provides for the interagency coordination of global change activities, including research on how the climate is likely to change and on the potential consequences for the environment and society. Responsibility is assigned to the Executive Office of the President and is implemented under the guidance of the Office of Science and Technology Policy (OSTP). To implement this coordination, OSTP has established several interagency subcommittees. The U.S. Global Change Research Program (USGCRP) provides a framework for coordination of research to reduce uncertainties about climate change and potential impacts on climate, ecosystems, natural resources, and society (see Chapter 8). A number of the activities of the other subcommittees are also related to the issues of vulnerability and adaptation to global climate change:

- *Natural Disaster Reduction*—This subcommittee promotes interagency efforts to assemble and analyze data and information about the occurrence and vulnerability of the United States to a wide range of weather- and climate-related events. Through its participating agencies, the subcommittee is also promoting efforts by communities, universities, and others to increase their preparation for, and resilience to, natural disasters. In that climate change may alter the intensity, frequency, duration and location of such disasters, enhancing resilience and flexibility will assist in coping with climate change.

- *Air Quality*—This subcommittee promotes interagency efforts to document and investigate the factors affecting air quality on scales from regional and subcontinental to intercontinental and global, focusing particularly on tropospheric ozone and particulate matter, both of which contribute to climate change as well as being affected by it.
- *Ecological Systems*—This subcommittee promotes interagency efforts to assemble information about ecological systems and services and their coupling to society and environmental change. It is sponsoring assessments that document the current state of the nation's ecosystems, and that provide scenarios of future conditions under various management and policy options, providing a baseline for the National Assessment studies concerning how ecosystems are likely to change over the long term.

Individual Agency Research Activities

In addition to their interagency activities, many of the USGCRP agencies have various responsibilities relating to the potential consequences of climate change and of consideration of responses and means for coping with and adapting to climate change.

U.S. Department of Agriculture

Research sponsored by the U.S. Department of Agriculture (USDA) focuses on understanding terrestrial systems and the effects of global change (including water balance, atmospheric deposition, vegetative quality, and UV-B radiation) on food, fiber, and forestry production in agricultural, forest, and range ecosystems. USDA research also addresses how resilient managed agricultural, rangeland, and forest ecosystems are to climate change and what adaptation strategies will be needed to adjust to a changing climate. Programs include long-term studies addressing the structure, function, and management of forest and grassland ecosystems; research in applied sciences, including soils, climate, food and fiber crops, pest management, forests and wildlife, and social sciences; implementation of ecosystem management on the national forests and grasslands; and human interaction with natural resources.

For example, U.S. Forest Service research has established a national plan of forest sustainability to continue to provide water, recreation, timber, and clean air in a changing environment. Two goals of this program are to improve strategies for sustaining forest health under multiple environmental stresses and to develop projections of future forest water quality and yield in light of potential changes in climate.

Similarly, research at the U.S. Agricultural Research Service (ARS) looks to determine the impacts of increased atmospheric CO_2 levels, rising temperatures, and water availability on crops and their interactions with other biological components of agricultural ecosystems. ARS also conducts research on characterizing and measuring changes in weather and the water cycles at local and regional scales, and determining how to manage agricultural production systems facing such changes.

National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration (NOAA) supports *in situ* and remote sensing and monitoring, research, and assessment to improve the accuracy of forecasts of weather and intense storms, and projections of climate change; to improve the scientific basis for federal, state, and local management of the coastal and marine environment and its natural resources; and to ensure a safe and productive marine transportation system. In addition to direct responsibilities for managing National Marine Sanctuaries and for protecting threatened, endangered, and trust resources, NOAA works with states to implement their coastal zone management plans and with regional councils to ensure sustained productivity of marine fisheries. Climate change and variability influence all areas of NOAA's responsibilities, both through direct effects and through intensification of other stresses, such as pollution, invasive species, and land and resource use.

U.S. Department of Health and Human Services

Through the National Institutes of Health, the Department of Health and Human Services sponsors research on a wide variety of health-related issues ranging from research on treatments for existing and emerging diseases to studies of risks from exposures to environmental stresses. For example, the National Institute of Environmental Health Sciences (NIEHS) conducts research on the effects of exposure to environmental agents on human health. The core programs of the NIEHS provide data and understanding for risk assessments due to changes in human vulnerability and exposures. Climate change raises issues of susceptibility to disease and needs for ensuring public health services. Changes in crop production techniques can increase human exposures to toxic agents and to disease vectors.

U.S. Department of the Interior

The U.S. Department of the Interior (DOI) is the largest manager of land and the associated biological and other natural resources within the United States. Its land management agencies, which include the Bureau of Land Management, the U.S. Fish and Wildlife Service, and the National Park Service, cumulatively manage over 180 million hectares (445 million acres) or 20 percent of the nation's land area for a variety of purposes, including preservation, tourism and recreation, timber harvesting, migratory birds, fish, wildlife, and a multiplicity of other functions and uses.

DOI's Bureau of Reclamation is the largest supplier and manager of water in the 17 western states, delivering water to over 30 million people for agricultural, municipal, industrial, and domestic uses. The Bureau also generates over a billion dollars worth of hydroelectric power and is responsible for multipurpose projects encompassing flood control, recreation, irrigation, fish, and wildlife. Management of land, water, and other natural resources is of necessity an exercise in adaptive management (IPCC 1991).

Research related to climate change conducted by DOI's U.S. Geological Survey includes efforts to identify which parts of the natural and human-controlled landscapes, ecosystems, and coastlines are at the highest risk under potential changes in climate and climate variability, water availability, and different land and resource management practices.

U.S. Department of Transportation

The U.S. Department of Transportation has recognized that many of the nation's transportation facilities and operations, which are now generally exposed to weather extremes, are also likely to be affected as the climate changes. Among a long list of potential impacts, sea level rise is likely to affect many port facilities and coastal airports; higher peak stream flows are likely to affect bridges and roadways, whereas lower summertime levels of rivers and the Great Lakes are likely to inhibit barge and ship traffic; and higher peak temperatures and more intense storms are likely to adversely affect pavements and freight movement. An assessment of the potential significance of changes for the U.S. transportation system and of guidelines for improving resilience is being organized.

U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency (EPA) works closely with other federal agencies, state and local governments, and Native American tribes to develop and enforce regulations under existing environmental laws, such as the Clean Air Act, the Clean Water Act, and the Safe Drinking Water Act. In line with EPA's mission to protect human health and safeguard the natural environment, EPA's Global Change Research Program is assessing the consequences of global change for human health, aquatic ecosystem health, air quality, and water quality. Recognizing the need for "place-based" information, these assessments will focus on impacts at appropriate geographic scales (e.g., regional, watershed). In addition, EPA is supporting three integrated regional assessments in the Mid-Atlantic, Great Lakes, and Gulf Coast regions. Finally, in support of these assessments, EPA laboratories and centers conduct research through intramural and extramural programs.

OTHER RESEARCH ACTIVITIES

In addition to federal activities, a number of local, state, and regional activities are underway. Many of these activities have developed from the various regional assessments sponsored by the USGCRP or with the encouragement of various federal agencies. In addition, the USGCRP and federal agencies have been expanding their education and outreach activities to the public and private sectors, as described in Chapter 9.

Recognizing our shared environment and the resources it provides, it is important that the nations of the world work together in planning and coordinating their steps to adapt to the changing climate projected for coming decades. As part of this effort, the United States has been co-chair of Working Group II of the Intergovernmental Panel on Climate Change, which is focused on impacts, adaptation, and vulnerability. For the IPCC's Fourth Assessment Report, the United States will co-chair IPCC Working Group I on Climate Science.

The United States is also a leader in organizing the Arctic Climate Impact Assessment (ACIA), which is being carried out under the auspices of the eight-nation Arctic Council to "evaluate and synthesize knowledge on climate variability, climate change, and increased ultraviolet radiation and their consequences.... The ACIA will examine possible future impacts on the environment and its living resources, on human health, and on buildings, roads and other infrastructure" (see http://www.acia.uaf.edu/). These and other assessments need to continue to be pursued in order to ensure the most accurate information possible for preparing for the changing climate.