

CHAPTER 1



## Introduction

**Lead Authors:** Peter Backlund, NCAR; Anthony Janetos, PNNL/Univ. Maryland; David Schimel, National Ecological Observatory Network

**Contributing Authors:** J. Hatfield, USDA ARS; M. Ryan, USDA Forest Service; S. Archer, Univ. Arizona; D. Lettenmaier, Univ. Washington

This report is an assessment of the effects of climate change on U.S. land resources, water resources, agriculture, and biodiversity. It is based on extensive examination of the relevant scientific literature, and is one of a series of 21 Synthesis and Assessment Products that are being produced under the auspices of the U.S. Climate Change Science Program (CCSP). The lead sponsor of this particular assessment product is the U.S. Department of Agriculture.

The purpose of this assessment and more broadly, of all the CCSP Scientific Assessment Products (SAPs) is to integrate existing scientific knowledge on issues and questions related to climate change that are important to policy and decision makers. The assessments are meant to support informed discussion and decision makers by a wide audience of potential stakeholders, including, for example, federal and state land managers, private citizens, private industry, and non-governmental organizations. The scientific research community is also an important stakeholder, as an additionally important feature of the SAPs is to inform decision making about the future directions and priorities of the federal scientific research programs by pointing out where there are important knowledge gaps. It is a goal of the SAPs that they not only be useful and informative scientific documents, but that they are also accessible and understandable to a more general, well-informed public audience. The team of authors was selected by the agencies after asking for public comment, and it includes

scientists and researchers from universities, non-governmental organizations, and government agencies, coordinated by the National Center for Atmospheric Research (NCAR). The team has reviewed hundreds of peer-reviewed papers, guided by a prospectus agreed upon by the CCSP agencies (see Appendix C).

### Intent of this Report

Strong scientific consensus highlights that anthropogenic effects of climate change are already occurring and will be substantial (IPCC). A recent U.S. government analysis (GAO) shows that that U.S. land management agencies are not prepared to address this issue. This analysis also highlights the need for assessment of climate change impacts on U.S. natural resources and assessment of monitoring systems needed to provide information to support effective decision making about mitigation and adaptation in periods of potentially rapid change. This report addresses this issue by providing an assessment specific to U.S. natural resources in agriculture, land resources, water resources, and biodiversity, and by assessing the ability of existing monitoring systems to aid decision making. The report documents that (1) numerous, substantial impacts of climate change on U.S. natural resources are already occurring, (2) that these are likely to become exacerbated as warming progresses, and (3) that existing monitoring systems are insufficient to address this issue.

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### Scope of this Report

The overall scope of the report has been determined by agreement among the CCSP agencies. Important features of the scope include the topics to be addressed:

#### Agriculture

- Cropping systems
- Pasture and grazing lands
- Animal management

#### Land Resources

- Forests
- Arid lands

#### Water Resources

- Quantity, availability, and accessibility
- Quality

#### Biodiversity

- Species diversity
- Rare and sensitive ecosystems

Equally important are the elements of the climate change problem that are not addressed by this report. Some key issues, such as climate impacts on freshwater ecosystems, did not receive extensive attention. This is mainly due to timing and length constraints – it does not represent a judgment on the part of the authors that such impacts are not important. In addition, while the report was specifically asked to address issues of climate impacts, it was not asked to address the challenge of what adaptation and management strategies exist, their potential effectiveness, and potential costs. While these topics are acknowledged to be important in the scientific literature (Parsons et al.; Granger Morgan et al.; U.S. National Assessment), they are the subject of another of the CCSP Synthesis and Assessment Products (4.4). Nevertheless, the information synthesized in this report is meant to be of use to stakeholders concerned with planning, undertaking, and evaluating the effectiveness of adaptation options.

This report also deals almost exclusively with biological, ecological, and physical impacts of climate change. With the exception of some information in agricultural systems, market impacts on natural resources are not discussed, nor are the potential costs or benefits of changes

in the management of natural resources. We recognize that this leaves an incomplete picture of the overall impacts of climate change on those resources that the nation considers significant. Again, however, further consideration of economic effects requires a firm foundation in understanding the biological, ecological, and physical impacts.

### Guiding Questions for this Report

This synthesis and assessment report builds on an extensive scientific literature and series of recent assessments of the historical and potential impacts of climate change and climate variability on managed and unmanaged ecosystems and their constituent biota and processes. It discusses the nation's ability to identify, observe, and monitor the stresses that influence agriculture, land resources, water resources, and biodiversity, and evaluates the relative importance of these stresses and how they are likely to change in the future. It identifies changes in resource conditions that are now being observed, and examines whether these changes can be attributed in whole or part to climate change. It also highlights changes in resource conditions that recent scientific studies suggest are most likely to occur in response to climate change, and when and where to look for these changes. The assessment is guided by five overarching questions:

**What factors influencing agriculture, land resources, water resources, and biodiversity in the United States are sensitive to climate and climate change?**

**How could changes in climate exacerbate or ameliorate stresses on agriculture, land resources, water resources, and biodiversity?**

**What are the indicators of these stresses?**

**What current and potential observation systems could be used to monitor these indicators?**

**Can observation systems detect changes in agriculture, land resources, water resources, and biodiversity that are caused by climate change, as opposed to being driven by other causal activities?**

### Ascribing Confidence to Findings

The authors of this document have used language agreed to by the CCSP agencies to describe their confidence in findings that project future climate changes and impacts, as shown in Figure 1.1. The intent is to use a limited set of terms in a systematic and consistent fashion to communicate clearly with readers. The use of these terms represents the qualitative judgment of the authors of this document; much of the underlying literature does not use such a lexicon. Unless explicitly describing a formal statistical analysis, the use of these terms by the authors of this assessment should be treated as a statement of their expert judgment in the confidence of our findings and conclusions. There are cases where we have not applied the agreed terminology because we felt it was not an accurate representation of work published by others.

### Time Horizon for this Report

Climate change is a long-term issue and will affect the world for the foreseeable future. Many studies of climate change have focused on the next 100 years and model projections out to 2100 have become the de facto standard, as reported in the assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC) and many other documents. In this report, however, the focus is on the mid-term future. Key results are reported out to 100 years to frame the report, but the emphasis is on the next 25-50 years.

This mid-term focus is chosen for several reasons. First, for many natural resources, planning and management activities already address these time scales through the development of long-lived infrastructure, forest rotations, and other

significant investments. Second, we will experience significant warming from greenhouse gas emissions that have already occurred, regardless of the effectiveness of any emissions reduction activities. And most emission scenarios for the next few decades do not significantly diverge from each other because it will take decades to make major changes in energy infrastructure in the U.S. and other nations. As a result, high- and low-emission scenarios only begin to separate strongly in the 2030s-2050s. As emissions diverge, so do climate projections, and uncertainty about future climates rapidly becomes more pronounced. Averaging over climate models, a rate of a few tenths of a degree per decade can be assumed likely for the next two to four decades.

### Global Climate Context

There is a robust scientific consensus that human-induced climate change is occurring. The recently released Fourth Assessment Report of the IPCC (IPCC AR4) states with “very high confidence,” that human activity has caused the global climate to warm. Many well-documented observations show that fossil fuel burning, deforestation, and other industrial processes are rapidly increasing the atmospheric concentrations of CO<sub>2</sub> and other greenhouse gases. The IPCC report describes an increasing body of observations and modeling results, summarized below, which show that these changes in atmospheric composition are changing the global climate and beginning to affect terrestrial and marine ecosystems.

The global-average surface temperature increased by about 0.6°C over the 20th century. Global sea level increased by about 15-20 cm during this period.

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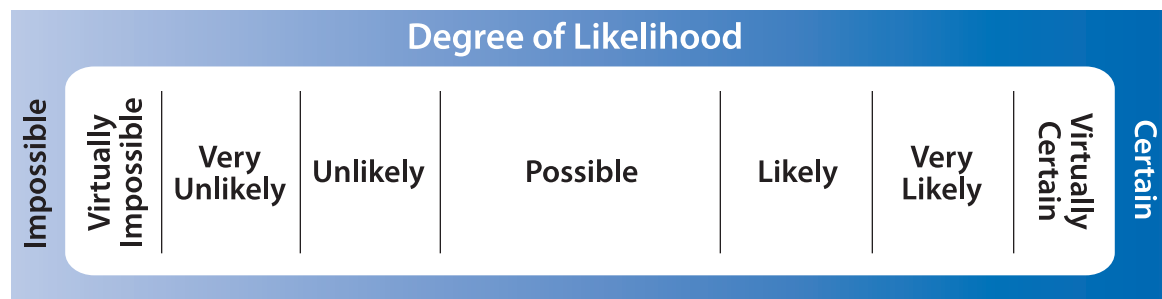


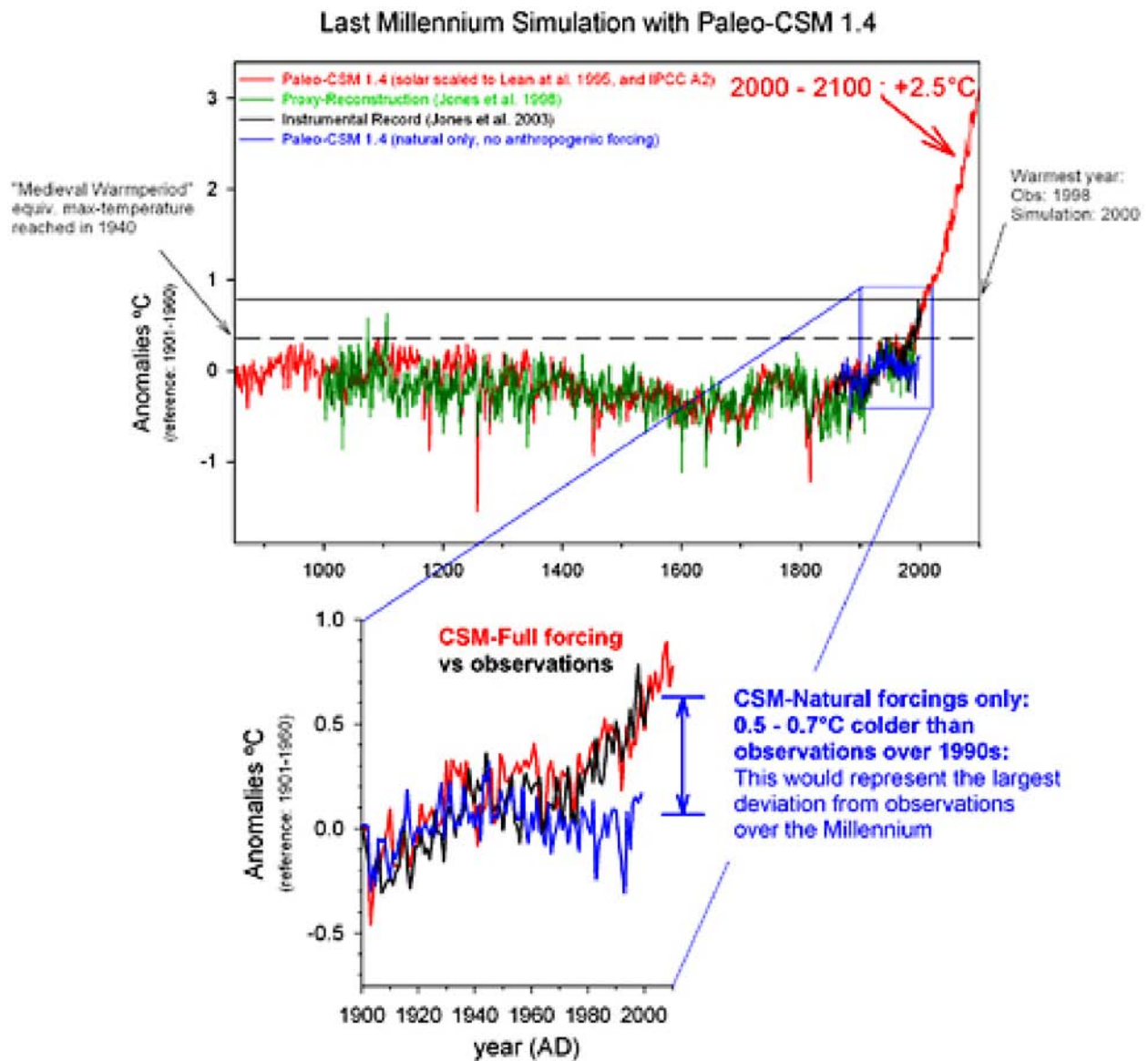
Figure 1.1 Language for discussing confidence in findings.

Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000 meters, and that the ocean has been absorbing more than 80 percent of the heat added to the climate system.

Long-term temperature records from ice sheets, glaciers, lake sediments, corals, tree rings, and historical documents show that 1995-2004 was the warmest decade worldwide in the last 1-2,000 years. Nine of the 10 warmest years on record occurred since 1996.

Global precipitation over land increased about 2 percent over the last century, with considerable variability by region (Northern Hemisphere precipitation increased by about 5 to 10 percent during this time, while West Africa and other areas experienced decreases).

Mountain glaciers are melting worldwide, Greenland's ice sheet is melting, the extent and thickness of Arctic sea ice is declining, and lakes and rivers freeze later in the fall and melt earlier in the spring. The growing season



**Figure 1.2** Temperatures of the Last Millennium and the Next Century. The effects of historical reconstructions of solar variability and volcanic eruptions were modeled using an NCAR climate model and compared to several reconstructions of past temperatures. The model reproduces many temperature variations of the past 1,000 years, and shows that solar and volcanic forcing has been a considerable impact on past climate. When only 20th century solar and volcanic data are used, the model fails to reproduce the recent warming, but captures it well when greenhouse gases are included.



in the Northern Hemisphere has lengthened by about 1 to 4 days per decade in the last 40 years, especially at high latitudes.

The ranges of migrating birds, and some fish and insect species are changing. Tropical regions are losing animal species, especially amphibians, to warming and drying.

Although much (but not all) of recent increases have been in nighttime maximum temperatures rather than daytime maxima, the expectation for the future is that daytime temperatures will become increasingly responsible for higher overall average temperatures.

Change and variability are persistent features of climate, and the anthropogenic climate change now occurring follows millennia of strictly natural climate changes and variability. Paleoclimate records, including natural archives in tree rings, corals, and glacial ice, now show that the climate of the last millennium has varied significantly with hemispheric-to-global changes in temperature and precipitation resulting from the effects of the sun, volcanoes, and the climate system's natural variability (Ammann et al. 2007). The anthropogenic changes now being observed are superimposed on this longer-term, ongoing variability, some of which can be reproduced by today's advanced climate models. Importantly, the model that captures the past thousand years of global temperature patterns successfully (Figure 1.2) using only solar and volcanic inputs does not accurately simulate the 20th century's actual, observed climate unless greenhouse gases are factored in (Ammann et al. 2007).

It is also clear that human influences will continue to alter Earth's climate throughout the 21st century. The IPCC AR4 describes a large body of modeling results, which show that changes in atmospheric composition will result in further increases in global average temperature and sea level, and continued declines in snow cover, land ice, and sea ice extent. Global average rainfall, variability of rainfall, and heavy rainfall events are projected to increase. Heat waves in Europe, North America, and other regions will become more intense, more frequent, and longer

lasting. It is very likely that the rate of climate change in the 21st century will be faster than that seen in the last 10,000 years. The IPCC AR4 contains projections of the temperature increases that would result from a variety of different emissions scenarios:

If atmospheric concentration of CO<sub>2</sub> increases to about 550 parts per million (ppm), global average surface temperature would likely increase by about 1.1-2.9°C by 2100.

If atmospheric concentration of CO<sub>2</sub> increases to about 700 ppm, global average surface temperature would likely increase about 1.7-4.4°C by 2100.

If atmospheric concentration of CO<sub>2</sub> increases to about 800 ppm, global average surface temperature would likely increase about 2.0-5.4°C by 2100.

Even if atmospheric concentration of CO<sub>2</sub> were stabilized at today's concentrations of about 380 ppm, global average surface temperatures would likely continue to increase by another 0.3–0.9°C by 2100.

### U.S. Climate Context

Records of temperature and precipitation in the United States show trends that are consistent with the global-scale changes discussed above. The United States has warmed significantly overall, but change varies by region (Figure 1.3). Some parts of the United States have cooled, but Alaska and other northern regions have warmed significantly. Much of the eastern and southern U.S. now receive more precipitation than 100 years ago, while other areas, especially in the Southwest, now receive less (Figure 1.4).

The scenarios of global temperature change discussed in the global climate context section above would result in large changes in U.S. temperatures and precipitation, with considerable variation by region. Figure 1.5, which is based on multiple model simulations, show how IPCC global scenario A1B, generally considered a moderate emissions growth scenario, would affect U.S. temperatures and precipitation by 2030. The projected temperature increases range



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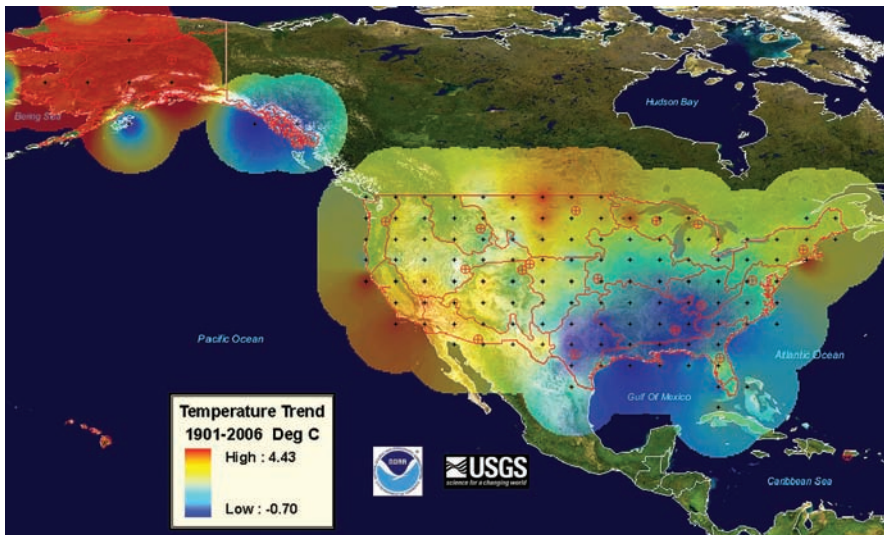
from approximately 1°C in the southeastern United States, to more than 2°C in Alaska and northern Canada, with other parts of North America having intermediate values.

Although precipitation increases are anticipated for large areas of the U.S., it is important to note this does not necessarily translate into more available moisture for biological and ecological processes. Higher temperatures increase evapotranspirative losses to the atmosphere, and the

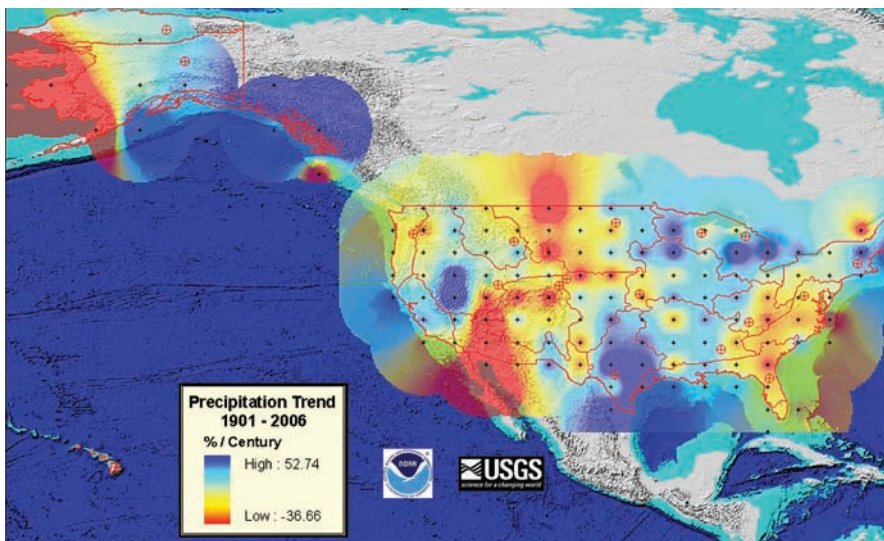
relative balance of the two factors on average in the U.S. leads to less moisture in soils and surface waters for organisms or ecosystems to utilize both now and in the future.

The average temperature and precipitation are not the only factors that affect ecosystems. Extreme climate conditions, such as droughts, heavy rainfall, snow events, and heat waves affect individual species and ecosystems structure and function. Change in the incidence of

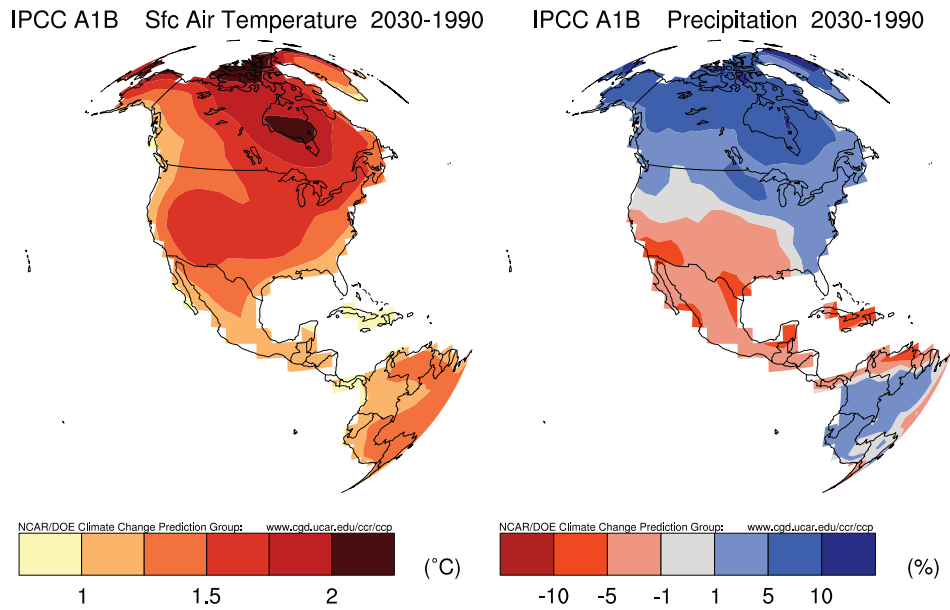
extreme events could thus have major impacts on U.S. ecosystems and must be considered when assessing vulnerability to and impacts of climate change. Figure 1.6 shows how the IPCC A1B scenario will change the incidence of heat waves and warm nights by approximately 2030. Figure 1.7 shows projected changes in frost days and growing season.



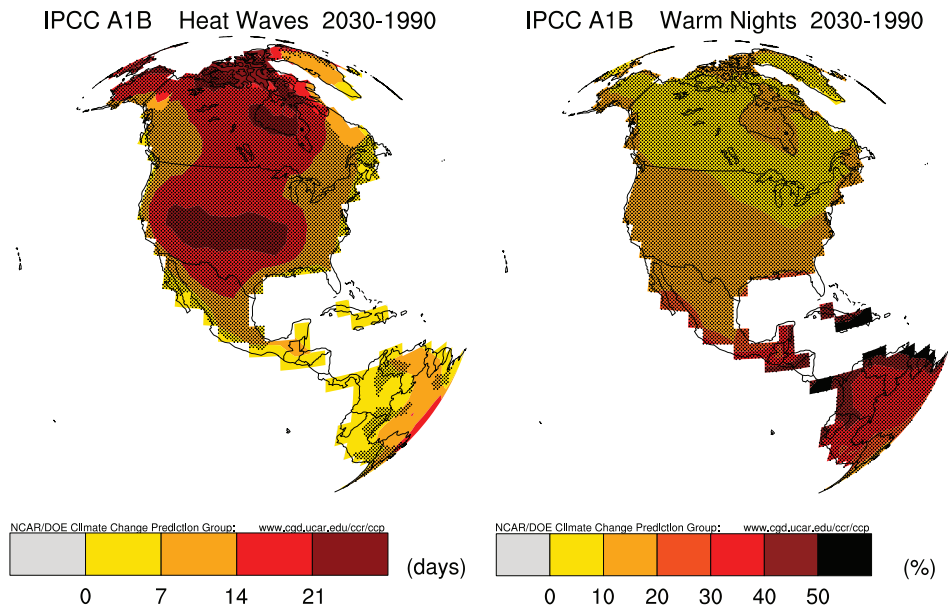
**Figure 1.3** Mapped trends in temperature across the lower 48 states and Alaska. These data, which show the regional pattern of U.S. warming, are averaged from weather stations across the country using stations that have as complete, consistent, and high quality records as can be found. Courtesy of NOAA’s National Climate Data Center and the U.S. Geological Survey.



**Figure 1.4** Precipitation changes over the past century from the same weather stations as for temperature. The changes are shown as percentage changes from the long-term average. Courtesy of NOAA’s National Climate Data Center and the U.S. Geological Survey.



**Figure I.5** U.S. Temperature and Precipitation Changes by 2030. This figure shows how U.S. temperatures and precipitation would change by 2030 under IPCC emissions scenario A1B, which would increase the atmospheric concentration of greenhouse gases to about 700 parts per million by 2100 (this is roughly double the pre-industrial level). The changes are shown as the difference between two 20-year averages (2020-2040 minus 1980-1999). These results are based on simulations from nine different climate models from the IPCC AR4 multi-model ensemble. The simulations were created on supercomputers at research centers in France, Japan, Russia, and the United States. Adapted by Lawrence Buja and Julie Arblaster from Tebaldi et al. 2006: *Climatic Change, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, Climatic Change, 79:185-211.*



**Figure I.6** Simulated U.S. Heat Wave Days and Warm Nights in 2030. The left panel shows the projected change in number of heat wave days (days with maximum temperature higher by at least 5°C (with respect to the climatological norm)). The right panel shows changes in warm nights (percent of times when minimum temperature is above the 90th percentile of the climatological distribution for that day). Both panels show results for IPCC emissions scenario A1B, which would increase the atmospheric concentration of greenhouse gases to about 700 parts per million by 2100 (this is roughly double the pre-industrial level). The changes are shown as the difference between two 20-year averages (2020-2040 minus 1980-1999). Shading indicates areas of high inter-model agreement. These results are based on simulations from nine different climate models from the IPCC AR4 multi-model ensemble. The simulations were created on supercomputers at research centers in France, Japan, Russia, and the United States. Adapted by Lawrence Buja and Julie Arblaster from Tebaldi et al. 2006: *Climatic Change, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, Climatic Change, 79:185-211.*



**Ecological and Biological Context**

Climate variability and change have many impacts on terrestrial and marine ecosystems. Ecosystem responses to climate have implications for sustainability, biodiversity, and the ecosystem goods and services available to society. Some of these impacts affect the biological systems only, but some create further feedbacks to the climate system through greenhouse gas fluxes, albedo changes, and other processes.

Much research on terrestrial ecosystems and climate change has focused on their role as carbon sources or sinks. The observation that atmospheric CO<sub>2</sub> was increasing more slowly than expected from fossil fuel use and ocean

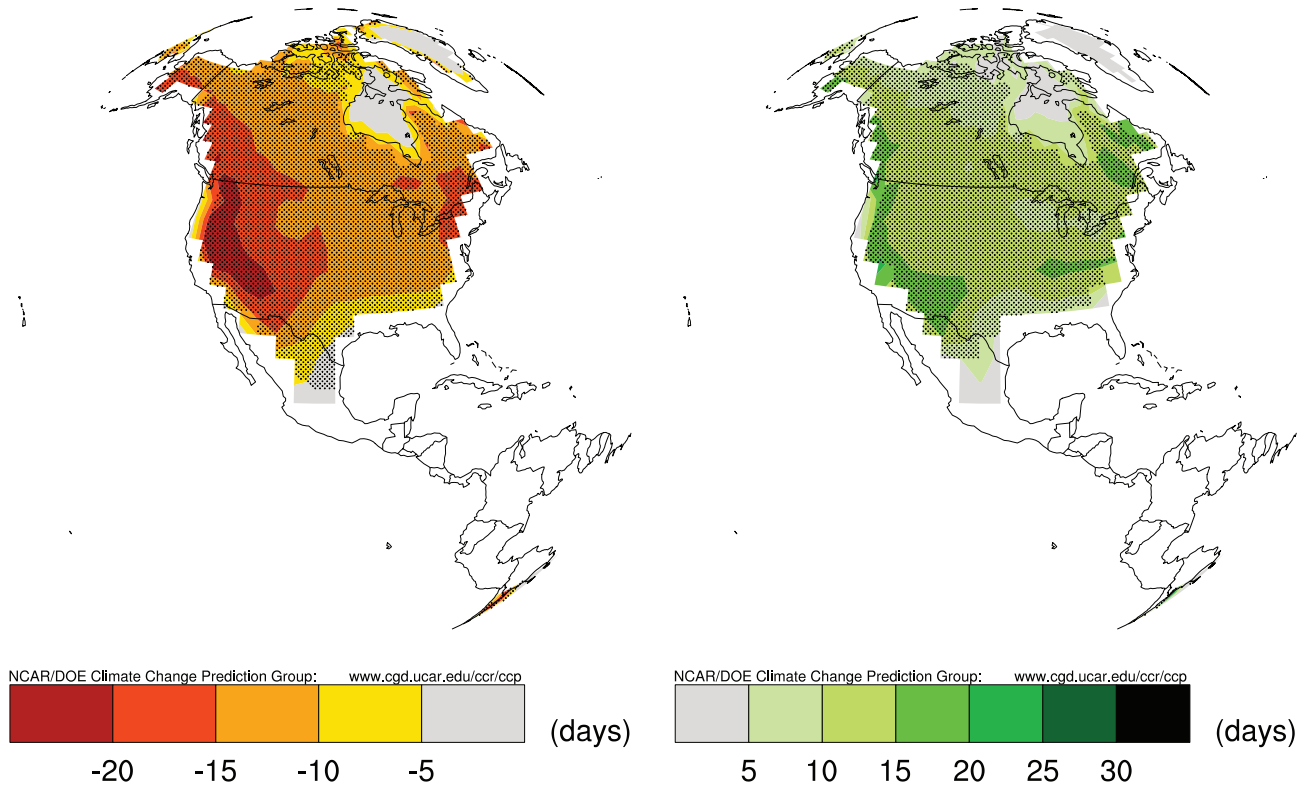
uptake led to the speculation of a “missing sink,” and the conclusion that increased plant photosynthesis was due to elevated atmospheric CO<sub>2</sub> (Gifford et al. 1994). It is now evident that several mechanisms, and not just CO<sub>2</sub> fertilization, contribute to the ‘missing sink’ (Field et al. 2007). These mechanisms include recovery from historic land use, fertilizing effects of nitrogen in the environment, expansion of woody vegetation ranges, storage of carbon in landfills and other depositional sites, and sequestration in long-lived timber products (Schimel et al. 2001).

Responses of photosynthesis and other processes that contribute to overall plant growth to warming are nonlinear. Each process (e.g.,



IPCC A1B Frost days 2030-1990

IPCC A1B Growing season 2030-1990



**Figure 1.7** Changes in U.S. Frost days and Growing season by 2030. This figure shows decreases in frost days and increases in growing season length that would occur by about 2030 if the world follows IPCC emissions scenario A1B, which would increase the atmospheric concentration of greenhouse gases to about 700 parts per million by 2100 (this is roughly double the pre-industrial level). The changes are shown as the difference between two 20-year averages (2020-2040 minus 1980-1999). Shading indicates areas of high inter-model agreement. These results are based on simulations from nine different climate models from the IPCC AR4 multi-model ensemble. The simulations were created on supercomputers at research centers in France, Japan, Russia, and the United States. Adapted by Lawrence Buja and Julie Arblaster from Tebaldi et al. 2006: Climatic Change, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, *Climatic Change*, 79:185-211.



photosynthesis, respiration) typically has its own optimal response to temperature, which then decreases as temperatures change either below or above that optimum. The response of plants from different ecosystems is usually adapted to local conditions. Extreme hot and cold events affect photosynthesis and growth and may reduce carbon uptake or even cause mortality. Warming can lead to either increased or decreased plant growth, depending on the balance of the response of the individual processes.

Comprehensive analyses show that climate change is already causing the shift of many species to higher latitudes and/or altitudes, as well as changes in phenology. Not all species can successfully adjust, and some models suggest that biomes that are shifting in a warm, high-CO<sub>2</sub> world lose an average of a tenth of their biota.

Climate will affect ecosystems through fire, pest outbreaks, diseases, and extreme weather, as well as through changes to photosynthesis and other physiological processes. Disturbance regimes are a major control of climate-biome patterns. Fire-prone ecosystems cover about half the land area where forests would be expected, based on climate alone, and lead to grasslands and savannas in some of these areas. Plant pathogens, and insect defoliators are pervasive as well, and annually affect more than 40 times the acreage of forests in the United States damaged by fire. Disturbance modifies the climatic conditions where a vegetation type can exist.

While much of the ecosystems and climate change literature focuses on plants and soil processes, significant impacts on animal species are also known. A substantial literature documents impacts on the timing of bird migrations, on the latitudinal and elevational ranges of species and on more complex interactions between species, e.g., when predator and prey species respond to climate differently, breaking their relationships (Parmesan and Yohe 2003). The seasonality of animal processes may also respond to changes in climate, and this effect can have dramatic consequences, as occurs, for example, with changes in insect pest or pathogen-plant host interactions. Domestic animals also respond

significantly to climate, both through direct physiological impacts on livestock, and through more complex effects of climate on livestock and their habitats.

Marine and coastal ecosystems are similarly sensitive in general to variability and change in the physical climate system, and in some cases directly to atmospheric concentrations of carbon dioxide. Fish populations in major large marine biomes are known to shift their geographic ranges in response to specific modes of climate variation, such as the Pacific Decadal Oscillation and the North Atlantic Oscillation, and there have been shifts in geographical range of some fish species in response to surface water warming over the past several decades on both West and East coasts of North America. Sub-tropical and tropical corals in shallow waters have already suffered major bleaching events that are clearly driven by increases in sea surface temperatures, and increases in ocean acidity, which are a direct consequence of increases in atmospheric carbon dioxide, are calculated to have the potential for serious negative consequences for corals.

Many studies on climate impacts on ecosystems look specifically at impacts only of variation and change in the physical climate system and CO<sub>2</sub> concentrations. But there are many factors that affect the distribution, complexity, make-up, and performance of ecosystems. Disturbance, pests, invasive species, deforestation, human management practices, overfishing, etc., are powerful influences on ecosystems. Climate change impacts are but one of many such features, and need to be considered in this broader context.

### Attribution of Ecosystem Changes

It is important to note that the changes due to climate change occur against a background of rapid changes in other factors affecting ecosystems. These include changing patterns of land management, intensification of land use and exurban development, new management practices (e.g., biofuel production), species invasions and changing air quality (Lodge et al. 2006). Because many factors are affecting ecosystems simultaneously, it is difficult and in some cases impossible to factor out the magnitude of each

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The changes that are likely to occur will continue to have significant effects on the ecosystems of the United States, and the services those ecosystems provide.



impact separately. In a system affected by, for example, temperature, ozone, and changing precipitation, assigning a percentage of an observed change to each factor is generally impossible. Research on improving techniques for separating influences is ongoing, but in some cases drivers of change interact with each other, making the combined effects different from the sum of the separate effects. Scientific concern about such multiple stresses is rising rapidly.

### Summary

The changes in temperature and precipitation over the past century now form a persistent pattern and show features consistent with the scientific understanding of climate change. For example, scientists expect larger changes near the poles than near the equator. This pattern can be seen in the dramatically higher rates of warming in Alaska compared to the rest of the country. Most of the warming is concentrated in the last decades of the century. Prior to that, large natural variations due to solar and volcanic effects were comparable in magnitude to the then-lower greenhouse gas effects. These natural swings sometimes enhanced and sometimes hid the effects of greenhouse gases. The warming due to greenhouse gases is now quite large and the “signal” of the greenhouse warming has more clearly emerged from the “noise” of the planet’s natural variations. The effects of greenhouse gases have slowly accumulated, but in the past few years, their effects have become evident. Recent data show clearly both the trends in climate, and climate’s effects on many aspects of the nation’s ecology.

The changes that are likely to occur will continue to have significant effects on the ecosystems of the United States, and the services those ecosystems provide. The balance of this report will document some of the observed historical changes and provide insights into how the continuing changes may affect the nation’s ecosystems.