1 Introduction

This report is an assessment of the effects of climate change on U.S. land resources, water resources, agriculture, and biodiversity, based on extensive examination of the relevant scientific literature. It 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), which coordinates U.S. government climate change research across agencies. The lead sponsor of this particular assessment product is the U.S, Department of Agriculture. The team of authors includes scientists and researchers from universities, non-government organizations, and government agencies, coordinated by the National Center for Atmospheric Research (NCAR). They have reviewed and discussed hundreds of peer-reviewed papers, guided by a prospectus agreed upon by the CCSP agencies (*see appendix X*), to produce a synthesis of information on resource conditions, observation systems, and monitoring capabilities that can be used to gauge future change. Much of this literature was produced under the sponsorship of agency programs in the ecosystems, land use, and water research elements of the CCSP, and this assessment is properly seen as the product of ongoing support of research in these areas by the CCSP agencies.

1.1 Scope of this Report

As agreed by the CCSP agencies, the topics addressed in this product are:

- 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

1.2 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 our 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 resources 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?

1.3 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 below. Our intent is to use a limited set of terms in a consistent fashion.

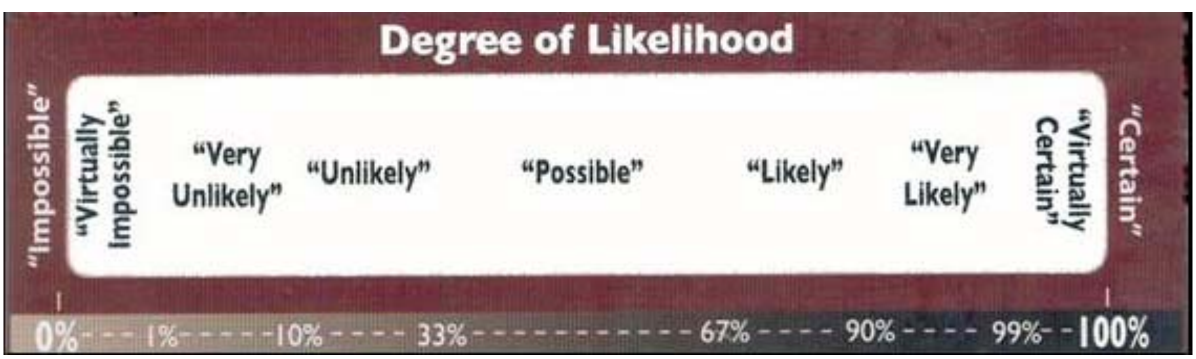


Figure 1.1 Language for Discussing Confidence in Findings

1.4 Time Horizon for this Report

Climate change is a long-term issue, and climate change will affect the world for the foreseeable future. Many studies of climate change have focused on the next 100 years as model projections out to 2100 have become a 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, we focus rather on the nearer-term future, the next 25-50 years. We report key results out to 100 years to frame the report, but we emphasize the coming decades.

This focus is chosen for two reasons. First, for many natural resources, planning and management already addresses these time scales through the development of long-lived infrastructure, forest rotations, and other significant investments. Second, climate projections are relatively certain over the next few decades. Emission scenarios for the next few decades do not diverge from each other very much because of the “inertia” of the energy system. Most projections of greenhouse gas emissions assume that it will take decades to make major changes in the energy infrastructure, and only begin to diverge rapidly until several decades have passed (30-50 years).

As a result, projections of high- and low-emission scenarios only begin to separate strongly in the 2030s-2040s, and climate scenarios then diverge slightly later. 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. As emissions diverge in the 2030s-2050s, so do climate projections and, as a result, uncertainty about future climates rapidly becomes larger.

This is captured in Figure 1.2 below, which shows that overall climate uncertainty is lowest in the mid-century. The near-term is affected by the weather forecast problem. Given a few tenths of a degree warming per decade, hard-to-forecast interannual variability (El Niño and similar phenomena) can contribute similar amounts of warming or cooling. Later in the century, variability between emission scenarios and resulting climate dominate and, since this depends on human choices and behavior, this is extremely hard to predict. Thus, the mid-term uncertainty is lowest. We focus this report on the mid-term, where the experience gained in observation studies likely remains relevant, where today’s management effects will remain relevant, and where the uncertainty is relatively low.

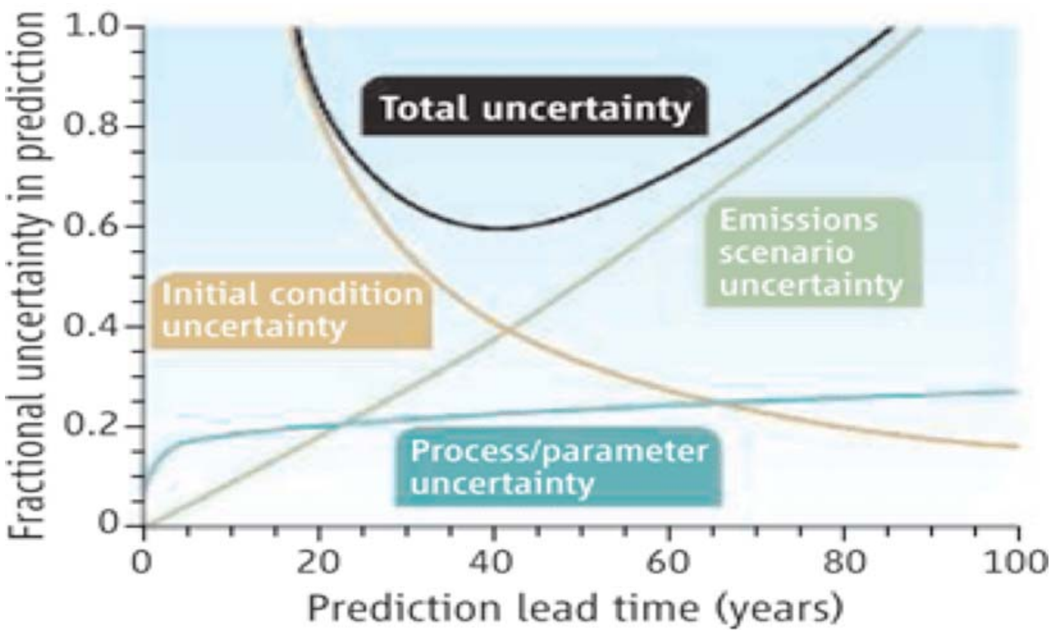


Figure 1.2 Uncertainty of Climate Projections: Contributions to uncertainty in the predicted decadal mean temperature vary with the lead time of the prediction. Climate predictions focusing on lead times of ~30 to 50 years have the lowest fractional uncertainty. From "A Changing Climate for Prediction," Peter Cox and David Stephenson, *Science*, 13 July 2007, pp. 207-208.

1.5 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 (Solomon et al. 2007). Many well-documented observations show that fossil fuel burning, deforestation, and other industrial processes are rapidly increasing the atmospheric concentrations of CO_2 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.
- 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 derived from ice sheets, glaciers, lake sediments, corals, tree rings, and historical documents show that 1995-2004 was the warmest decade worldwide in the last one to two thousand years. Nine of the 10 warmest years on record have occurred in the last decade.

- Global precipitation over land increased about two percent over the last century, with considerable variability by region (Northern Hemisphere precipitation increased by about five to 10 percnet during this time, while West Africa and other areas experienced decreases).
- Mountain glaciers are melting worldwide, the Greenland 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 has lengthened by about one to four days per decade in the last 40 years in the Northern Hemisphere, 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.

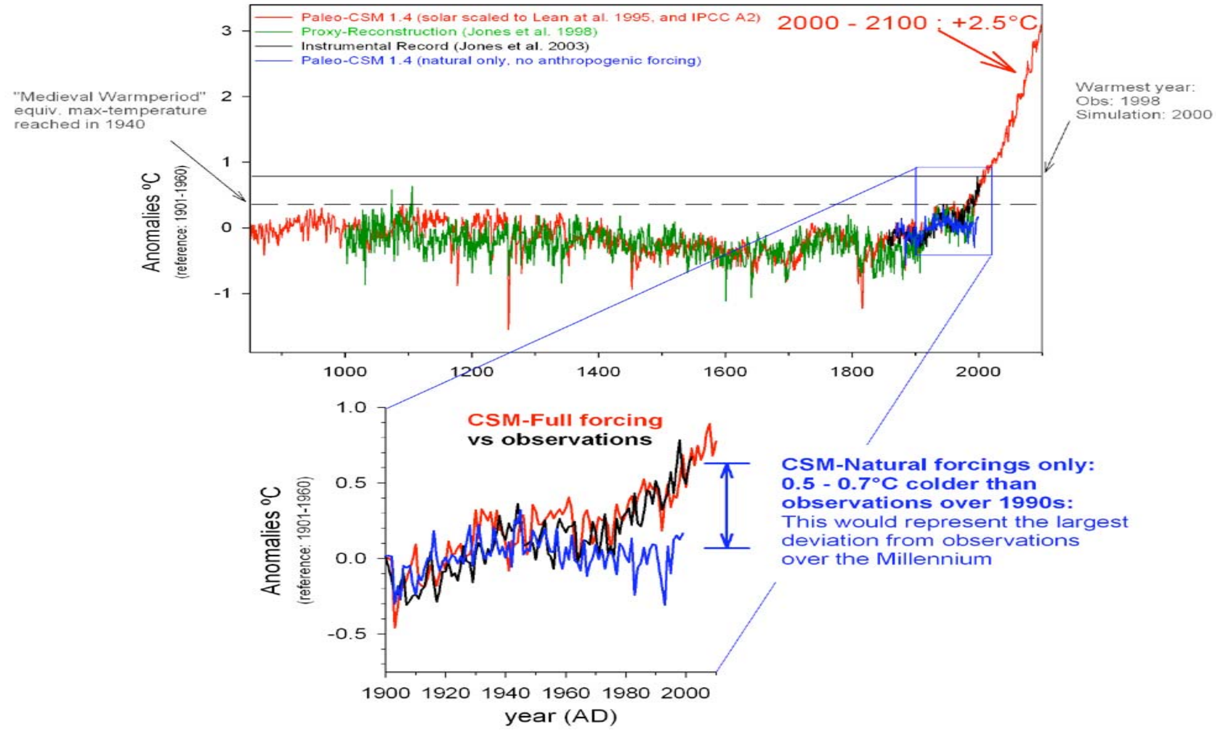


Figure 1.3 Temperatures of the Last Millennium and the Next Century. The effects of historical reconstructions of solar variability and volcanic eruptions were modeled using an NCAR climate model and compared to several reconstructions of past temperatures. The model reproduces many temperature variations 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 quite well when greenhouse gases are included.

Change is a persistent feature of climate, and the anthropogenic climate change now occurring follows on millennia of natural climate changes. We now know that the climate of the past thousand or so years has varied significantly with hemispheric-to-global variations in temperature and precipitation resulting from the effects of the sun, volcanoes, and the climate system’s natural variability (Ammann et al. 2007). This long-term variability is witnessed by many paleoclimate records, including natural archives in tree rings, corals, and glacial ice. Some of these historical variations can even be reproduced by today’s advanced climate models, which can convincingly capture the effects of solar variability and volcanoes over the past thousand years. Interestingly, the model that captures the past thousand years of global temperature patterns successfully (Figure 3) using only solar and volcanic inputs fails to simulate the 20th century unless greenhouse gases are factored in (Ammann et al. 2007).

Looking ahead, it is clear that human influences will continue to change 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 decline 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. We are very likely to experience a faster rate of climate change in the 21st century than seen in the last 10,000 years.

- If atmospheric concentration of CO2 increases to about 550 parts per million (ppm), global average surface temperature would likely increase by about 1.1 - 2.9ºC by 2100.
- If atmospheric concentration of CO2 increases to about 700 ppm, global average surface temperature would likely increase about 1.7 - 4.4ºC by 2100.
- If atmospheric concentration of CO2 increases to about 800 ppm, global average surface temperature would likely increase about 2.0 - 5.4º C by 2100.
- Even if atmospheric concentration of CO2 were stabilized at today's concentrations of about 380 ppm, global average surface temperatures would likely continue to increase by another 0.3 – 0.9ºC by 2100, as shown in Figure 1.4.

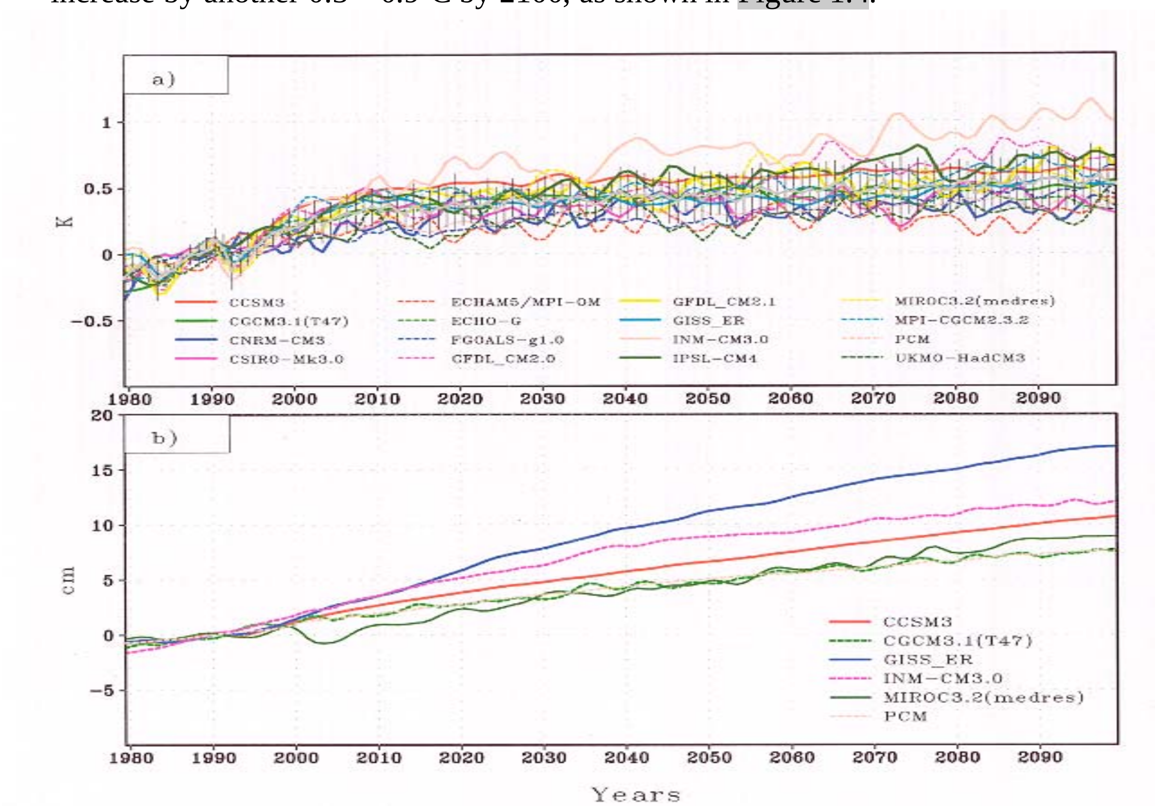


Figure 1.4 The Climate Change Commitment. A wide range of modeling studies indicates that substantial increases in temperature (panel a), and sea level rise (panel b) will occur over the next century even if atmospheric concentrations are stabilized at today's levels (*Science*,18 March 2005:Vol. 307. no. 5716, pp. 1766 - 1769).

1.6 U.S. Climate Context

Records of temperature and precipitation in the United States show changes that are consistent with the global-scale changes discussed above. The US has warmed up significantly overall, but change varies by region. (Figure 1.5). Parts have cooled, and Northern regions, especially Alaska, have warmed the most. Much of the Eastern and Southern U.S. now receive more precipitation than 100 years ago, while other areas, especially in the US Southwest, now receive less (Figure 1.6).

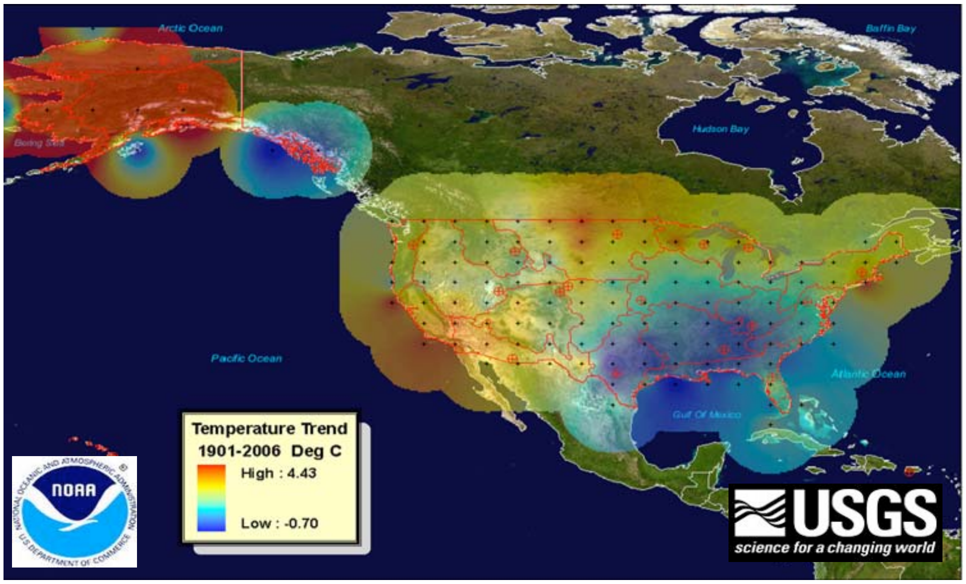


Figure 1.5 Mapped trends in temperature across the lower 48 states, and Alaska. These data, which show the regional pattern of US warming, are averaged from weather stations across the country using stations that have as complete, consistent, and high quality records as can be found. Data and mapping courtesy of NOAA's National Climate Data Center, and the U.S. Geological Survey.

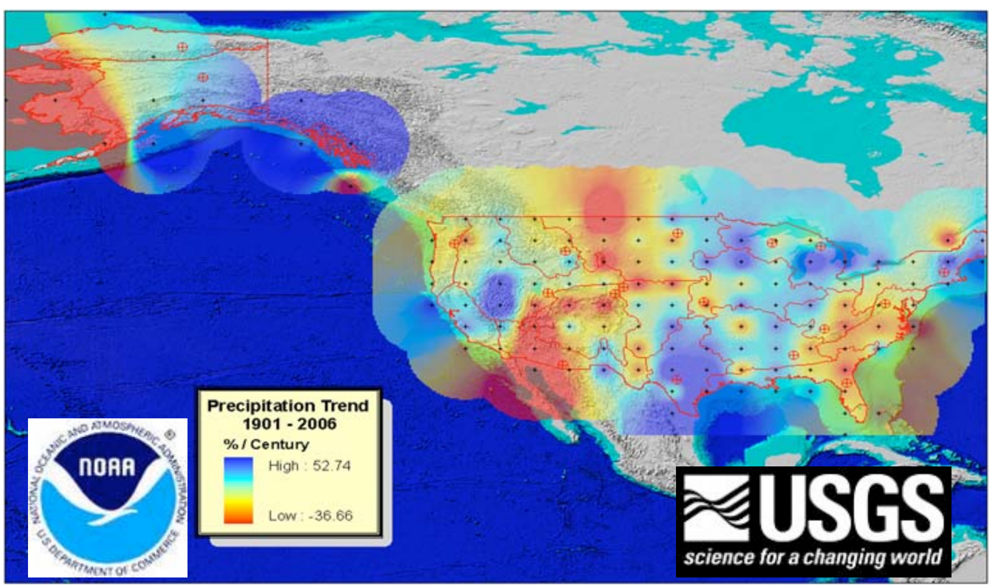
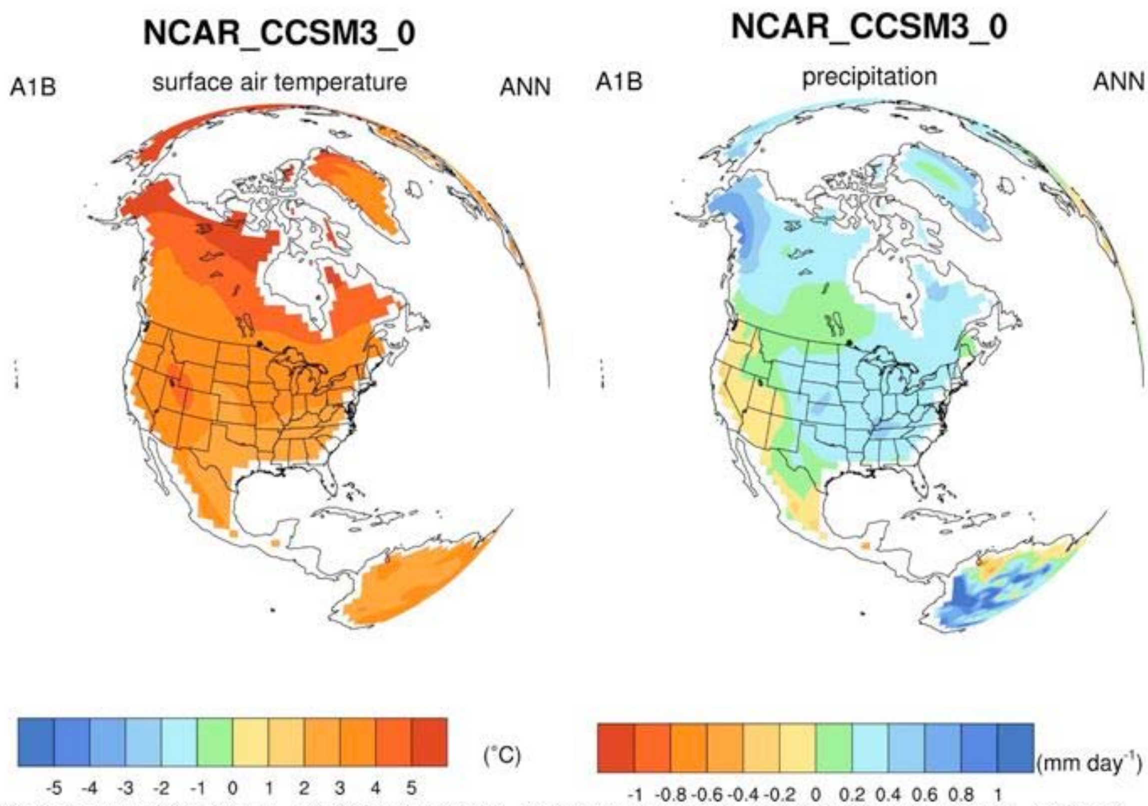


Figure 1.6 Precipitation changes over the past century from the same weather stations as for temperature. The changes are shown as percentage changes from the long-term average.

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. Below, Figure 8 shows results of an NCAR Community Climate System Model simulation for IPCC scenario A1B, generally considered a mid-range projection. The expected increases in average U.S. temperatures vary from 1-2°C more than 4°C – and remember that Alaska, for example, has already warmed by more than 2°C.



Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html

Figure 1.7 US Temperature and Precipitation Changes by 2100. This figure shows how U.S. temperature and precipitation would change by 2100 if the atmospheric concentration of greenhouse gases increases to about 700 parts per million, which is roughly double the pre-industrial level. The change is shown as the difference between two twenty-year averages (2080-2099 minus 1980-1999).

The average temperature and precipitation are not the only factors that matter for 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 9 shows how the U.S. temperature increases simulated by the NCAR Community Climate System Model (CCSM) for IPCC scenario A1B (a moderate emissions growth scenario) will result in an increased number of heat waves and warm nights in the last decade of this century. Figure 10 shows the expected change in heavy precipitation events.

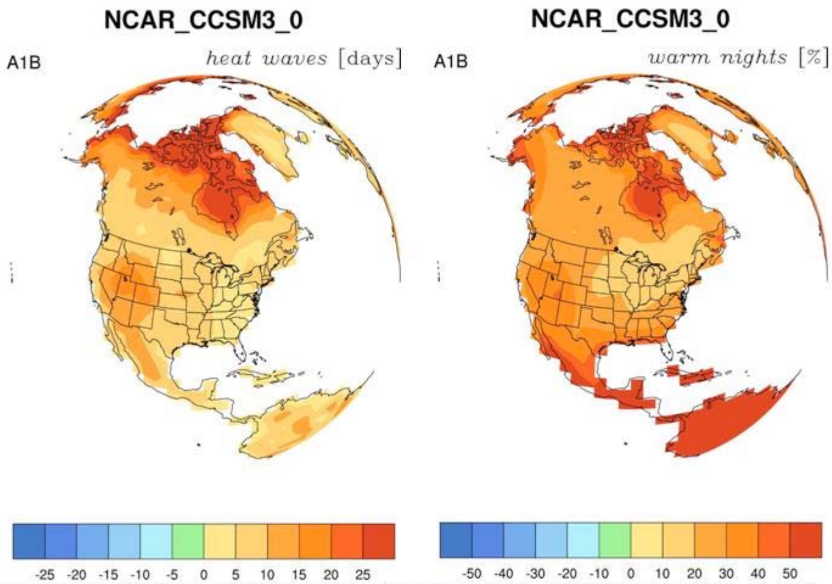


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Figure 1.8 Simulated US Heat Wave Days and Warm Nights in 2100. The left panel shows the expected change in number of heat wave days (days with maximum temperature higher by at least 5°C (with respect to the climatological norm) between 2000 and 2100. 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) between 2000 and 2100.

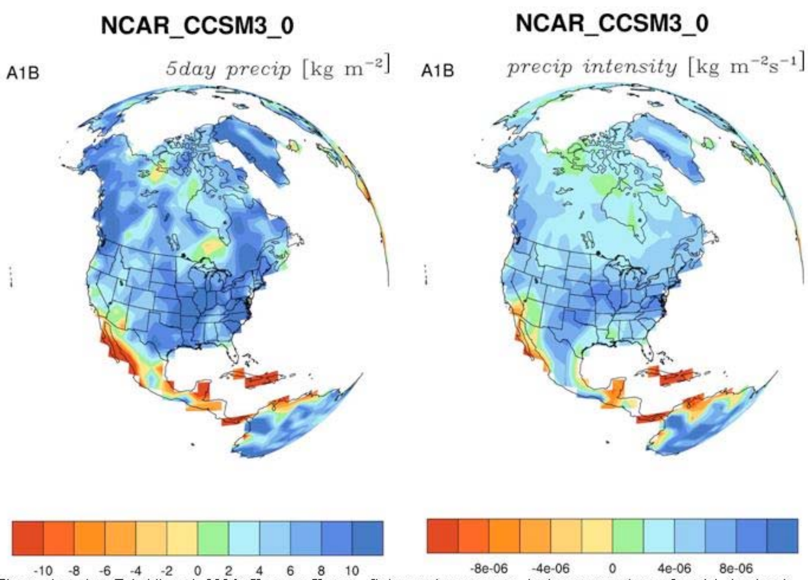

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Figure 1.9 Changes in US Precipitation by 2100. This figure shows increases in heavy rainfall expected for the United States if atmospheric concentrations of greenhouse increase to about 700 parts per million. The left panel shows changes in maximum 5-day precipitation totals, while the right panel shows a simple daily precipitation intensity index (annual total precipitation divided by the number of wet days).

1.7 Ecological and Biological Context

Climate has many impacts on terrestrial ecosystems, some of which create further feedbacks to climate through greenhouse gas fluxes, albedo changes, and other processes. Ecosystem responses to climate have implications for sustainability, biodiversity, and the ecosystem goods and services available to people. Much of the research on terrestrial ecosystems and climate change has focused on their role as carbon sources or sinks. The observation that atmospheric CO_2 was growing more slowly than expected from fossil fuel use and ocean uptake led to the conclusions of a "missing sink," and that increased plant photosynthesis was due to elevated atmospheric CO_2 (Gifford, RM. The Global Carbon Cycle: a Viewpoint on the Missing Sink. *Australian Journal of Plant Physiology* 21, 1–15).

It is now evident that several mechanisms, and not just CO_2 fertilization, play a role (Feedbacks of Terrestrial Ecosystems to Climate Change, (*Christopher B. Field, David B. Lobell, Halton A. Peters, Nona R. Chiariell*, Annual Review of Environment and Resources 2007 32). These include recovery from historic land use, fertilizing effects of nitrogen in the environment, expansion of woody vegetation, storage of carbon in landfills, reservoirs, and other depositional sites, and sequestration in long-lived timber products (Schimel D., House J.I., Hibbard K., Bousquet P., Peylin P., et al. (2001), Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems, *Nature*, 414, 169-172).

Responses of photosynthesis and growth to warming are nonlinear and typically rise to an optimum temperature, then decrease as it is exceeded. The response of plants from different ecosystems is usually adapted to local conditions, such that local warming increases photosynthesis under conditions that are cool relative to local conditions and decreases under conditions that are hot (relative to the local mean). Extreme hot and cold events affect photosynthesis and growth, and may reduce uptake or even cause mortality. Warming can lead to either increased or decreased plant growth.

Comprehensive analyses show that climate change can cause the shift of many species to higher latitudes and/or altitudes, as well as changes in phenology. Not all species can successfully adjust, and models show biomes that are shifting in a warm, high-CO_2 world lose an average of a tenth of their biota. When this is not offset by redundancy in function among species, linkages between climate and ecosystem function will break down.

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 United States forests damaged by fire. Disturbance modifies the climatic conditions where a vegetation type can exist.

The majority of studies on ecosystem responses and feedbacks to climate change treat the system as if factors external to the biosphere were affecting the system in a univariate way (i.e., by releasing CO_2 or warming the climate). More recent thinking recognizes that that deforestation, agriculture, and the spread of invasive species can influence or even dominate how systems respond to climate

While the vast majority 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 (Camille Parmesan and Gary Yohe, A globally coherent fingerprint of climate change impacts across natural systems, *Nature* 421, 37-42 2003) | doi:10.1038/). The seasonality of animal processes can also respond, 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. While the effects of climate change on animals has been less studied than effects on plants, the impacts on ecosystem goods and services from people may be as large or larger.

1.8 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, D.M., S. Williams, H. MacIsaac, K. Hayes, B. Leung, L. Loope, S. Reichard, R.N. Mack, P.B. Moyle, M. Smith, D.A. Andow, J.T. Carlton, and A. McMichael. 2006. Biological invasions: recommendations for policy and management [Position Paper for the Ecological Society of America]. Ecological Applications 16:2035-2054). Because many factors are affecting ecosystems simultaneously, it is difficult and in some cases impossible to factor out the magnitude of each 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 is ongoing on improved techniques for separating influences, 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.

1.9 Summary

The changes in temperature and precipitation over the past century now form a persistent pattern, and show features consistent with our 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. However, 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 our 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 our nation’s ecology.

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