CHAPTER 1

SCENARIOS FOR CLIMATE VARIABILITY AND CHANGE

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CHAPTER SUMMARY

Climate Context

Climate[1] provides the context for the environment and for many human activities — changes in the climate will thus have consequences for the environment and for human activities. While solar radiation is the primary energy source for maintaining the Earth's temperature, the atmospheric concentrations of water vapor, carbon dioxide (CO_2), methane (CH_4), and other gases determine the intensity of the natural greenhouse effect that currently keeps the Earth's surface temperature at about 58˚F (14˚C). Without this natural greenhouse effect, the Earth's surface temperature would be about 0˚F (about –18˚C), a temperature that would make the Earth uninhabitable for life as we know it. Over the last 150 years, combustion of coal, oil, and natural gas (collectively called fossil fuels), deforestation, plowing of soils, and various industrial activities have led, among other changes, to increases in the atmospheric concentrations of critical greenhouse gases. In particular, the CO_2 concentration has increased by about 30% and the CH_4 concentration by about 150%. The warming influence of these changes, amplified by associated increases in the atmospheric water vapor concentration, have intensified the natural greenhouse effect and initiated changes in the climate.

Climate of the Past Century

- Since the mid-1800s, the global average temperature has warmed by about 1˚F (about 0.6˚C). The Northern Hemisphere average temperature during the 1990s is almost 1.5˚F (about 0.9˚C) warmer than during the few centuries prior to the Industrial Revolution. While some of this warming may be due to an intensification of solar radiation and a small portion due to urban warming, a variety of analyses indicate that the current warming is too large to be explained by natural fluctuations alone. The observed magnitude, pattern, and timing of the global warming indicate that the rising concentrations of CO_2 and other greenhouse gases caused by human activities are contributing significantly to the recent warming.
- During the 20th century, the average temperature over the US increased by about 1˚F (0.6˚C), with some regions warming as much as 4˚F (about 2.4˚C) and some other regions showing slight cooling. In general, nighttime minimum temperatures rose more than daytime maximums, and wintertime temperatures rose more than those of summertime. Total annual precipitation also increased, with most of the increase occurring in heavy precipitation events.
- Reconstructions of the climate of the past thousand years using ice cores, tree rings, vegetation types, and other proxy measures suggest that the warming of the 20th century is unprecedented compared to natural variations prior to this century that were presumably caused by solar, volcanic, and other natural influences. In addition, the current warming is much more extensive and intense than the regional scale warming that peaked about 1000 years ago in Europe during what is referred to as the Medieval Warm Period. The recent warming is also far more than can be characterized as a recovery from the cool conditions centered in Europe and the North Atlantic region a few hundred years ago that are often referred to as the Little Ice Age. Looking back over the few thousand years for which we are able to provide some reconstruction of the temperature record, the current global warmth appears unprecedented.
- An ice-core record from Antarctica covering the past 420,000 years indicates that temperatures in that region have been up to about 10˚F (6˚C) colder than present values for about 90% of the

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[1] Throughout the National Assessment reports, the term "climate" is intended to include both climate variability and climate change. "Climate change" refers to long-term or persistent trends (over decades or more) or shifts in climate, while "climate variability" refers to short-term (generally decadal or less) climate fluctuations.

420,000-year period. During these cold periods, massive glaciers covered much of the land area of the Northern Hemisphere (e.g.,covering eastern North America with roughly a mile of ice to south of the Great Lakes), even though global temperatures were only several degrees colder. Evidence suggests that these variations have been driven primarily by changes in the seasonal and latitudinal distribution of solar radiation caused by cyclic variations in the Earth's orbit around the Sun,but amplified by a number of factors. These additional factors include changes in glacial height and extent,in ocean circulation, and in the atmospheric CO_2 and CH_4 concentrations that were apparently driven by the initial temperature change.

- The geological record indicates that the global climate has varied markedly over the past billion or more years. It appears that these natural variations resulted from changes in identifiable factors that still determine climatic conditions today. These factors include the amount of solar radiation and shape of the Earth's orbit around the Sun,the gas and particle composition of the atmosphere (which determines the efficiency of the absorption and reflection of incoming solar energy),the geographical pattern of land and ocean,the heights of mountains,the direction and intensity of ocean currents,the chaotic nature of the interactions among the atmosphere,land,and oceans,and more. The geological record clearly indicates that changes in these factors can cause significant changes in climate.

Climate of the Coming Century

- Projections of the expanding uses of coal,oil,and natural gas as sources of energy indicate that human activities will cause the atmospheric CO_2 concentration to rise to between 2 and 3 times its preindustrial level by the end of the 21st century unless very significant control measures are initiated. The concentrations of CH_4 and some other greenhouse gases are also projected to rise,whereas controls on chlorofluorocarbon emissions are expected to allow their concentrations to fall.
- The ongoing effects of past increases in the concentrations of greenhouse gases and the changes projected for the 21st century are very likely to cause the world to warm substantially in comparison to natural fluctuations that have been experienced over the past 1000 years. Model-based projections for a mid-range emissions scenario are that the global average temperature is likely to rise by about 2 to 6˚F (about 1.2 to 3.5˚C), with a central estimate of almost 4˚F (2.4˚C), by the end of the 21st century. The range of these estimates depends about equally on ranges in the estimates of climate sensitivity and of growth in fossil fuel emissions.
- For the mid-range emissions scenario,the projected warming is likely to be greater in mid and high latitudes than for the globe as a whole,and warming is likely to be greater over continents than over oceans. For this mid-range emissions scenario,the models used for this Assessment project that the average warming over the US would be in the range of about 5 to 9˚F (about 2.8 to 5˚C). However, given the wide range of possible emissions scenarios and uncertainties in the sensitivity of the climate to emissions scenarios,it is possible that the actual increase in US temperatures could be higher or lower than indicated by this range.
- A warming of 5 to 9˚F (2.8 to 5˚C) would be approximately equivalent to the annual average temperature difference between the northern and central tier of states,or the central and southern tier of states. Wintertime warming is projected to be greater than summertime warming and nighttime warming greater than daytime warming.
- Even though less warming is projected in summertime than in wintertime,the summertime

heat index, which combines the effects of heat and humidity into an effective temperature, is projected to rise anywhere from 5 to 15˚F (or even more for some scenarios) over much of the eastern half of the country, especially across the southeastern part of the country. If the projected rise in the heat index were to occur, summertime conditions for New York City could become like those now experienced in Atlanta, those in Atlanta like those now experienced in Houston, and those in Houston like those in Panama.

- The amount of rainfall over the globe is also very likely to rise because global warming will increase evaporation; however, the pattern of changes is likely to vary depending on latitude and geography as storm tracks are altered. Model projections of possible changes in annual precipitation across the US are generally mixed. Results from the two models used in the National Assessment tend to agree that there is likely to be an increase in precipitation in the southwestern US as Pacific Ocean temperatures increase, but do not provide a clear indication of the trend in the southeastern US.
- It is likely that the observed trends toward an intensification of precipitation events will continue. Thunderstorms and other intensive rain events are likely to produce larger rainfall totals. While it is not yet clear how the numbers and tracks of hurricanes will change, projections are that peak windspeed and rainfall intensity are likely to rise significantly.
- Although overall precipitation is likely to increase across the US, the higher temperatures will increase evaporation. Even with a modest increase in precipitation, the increase in the rate of evaporation is expected to cause reductions in summertime soil moisture, particularly in the central and southern US.
- Sea level, which has risen about 4 to 8 inches (10-20 cm) over the past century, is projected to increase by 5 to 37 inches (13-95 cm) over the coming century, with a central estimate of about 20 inches (50 cm). The range is so broad because of uncertainties concerning what might happen to the Antarctic and Greenland ice caps. To determine the amount of sea-level rise in particular regions, the global rise in sea level must be adjusted by the local rise or sinking of coastal lands.
- Limitations in scientific understanding mean that the potential exists for surprises or unexpected events to occur, for thresholds to be crossed, and for nonlinearities to develop. Such surprises have the potential of either amplifying projected changes or, in rarer cases, moderating the potential changes in climate. Examples might include amplified rates of sea-level rise if deterioration of the Greenland or Antarctic ice caps is accelerated; limited warming or perhaps even cooling in some regions if ocean currents and deep ocean overturning is suppressed; disappearance of Arctic sea ice over a few decades; sufficient warming of methane trapped in frozen soils to allow its release and subsequent amplification of the warming rate, etc. While such possibilities could cause large impacts, estimating the likelihood of their occurrence is presently highly problematic, making risk assessments quite difficult.

SCENARIOS FOR CLIMATE VARIABILITY AND CHANGE

INTRODUCTION

This National Assessment is charged with evaluating and summarizing the potential consequences of climate variability and change for the United States over the next 100 years (Dresler et al.,1998). Studies of the interactions of climate with both the environment and with societal activities show clearly that there are important interconnections. The very hot and dry conditions of the 1930s,coupled with poor land management practices,not only created Dust Bowl conditions on the Great Plains,but also led large numbers of people to migrate from the central US to settle in the Southwest and California. Drought conditions in 1988 and flood conditions in 1993 had devastating effects on many regions in the upper Mississippi River basin. Climate variations along the West Coast have led to years of drought (with subsequent fires) and of flood (with subsequent mudslides). It is these many interactions that have led to the focus on what will happen in the future as climate variations continue and as human activities believed to be capable of altering the climate continue.

The hypothesis that human activities could be influencing the global climate was first postulated more than a century ago (Arrhenius,1896) and has become much better developed during the 20th century (e.g.,beginning with papers by Callendar, 1938;Manabe and Wetherald,1975;Hansen et al., 1981 and continuing to include thousands of additional scientific papers). Assessments of the scientific literature to evaluate the basis for postulating that human activities are affecting the global climate have been undertaken by many groups,including the Intergovernmental Panel on Climate Change (IPCC,1990,1992,1996a),eminent advisory groups (PSAC,1965;NRC,1979,1983; NAS,1992), government agencies (e.g.,USDOE,1985a,1985b),professional societies (most recently, the American Geophysical Union,see Ledley et al.,1999),and prominent scientific researchers (e.g.,Mahlman, 1997). All of these analyses have come to similar conclusions,indicating that human activities are changing atmospheric composition in ways that are very likely to cause significant global warming during the 21st century. Results presented in this chapter draw upon the basis of scientific understanding described in these and related reports and the recent scientific literature,providing a limited set of citations that can be expanded upon by reference to these assessments.

Although these scientific studies indicate that the future will be different from the past,determining how different it will be and the significance of these differences presents a tremendous scientific challenge. The future will be affected by how the climate varies due to natural and human influences, how the environment may respond to climate change and to other factors,and how society may evolve due to a myriad of influences,including climate variability and change. Quite clearly, definitive predictions cannot be made,being too dependent on factors ranging from uncertainties introduced by our growing,but limited,understanding of the climate system to the complexities introduced by the pace of technological development and social evolution.

Given the seriousness and strength of the projections of climate change arising from the scientific community and from careful assessments,prudent risk management led Congress in 1990 to call for assessments of the potential impacts of climate change. During the 1990s,scientific assessments have focused on the global-scale consequences of human activities,leading to the conclusion that “the balance of evidence suggests a discernible human influence on the global climate”(IPCC,1996a). IPCC assessments of the consequences of climate change have also indicated that potentially important consequences could arise (IPCC,1996b,1996c). It was these global-scale findings that indicated both the need for and the possibility of being able to conduct an assessment of the potential consequences of climate variability and change for the United States.

As a basis for this Assessment,and in the context of the uncertainties inherent in looking forward 100 years,Assessment teams are pursing a three-pronged approach to considering how much the climate may change. The three approaches involve use of:(1) historical data to examine the continuation of trends or recurrence of past climatic extremes;(2)

comprehensive,state-of-the-science,model simulations to provide plausible scenarios for how the future climate may change;and (3) sensitivity analyses that can be used to explore the resilience of societal and ecological systems to climatic fluctuations and change. This chapter provides background and information concerning past and projected changes in climate needed to carry through the National Assessment goal of analyzing potential consequences for society and the environment.

It should be emphasized that this chapter does not attempt a full scientific review of the adequacy or accuracy of climate observations or climate simulations of the past or future. For such a review, this Assessment relies on the very comprehensive,international assessments being undertaken by the IPCC (e.g.,IPCC 1996a and the report now in preparation for release in 2001). Rather, this chapter provides information needed to understand and explain the analyses of the regional to national scale impact studies that are described in this National Assessment report and the supporting regional and sector reports. In presenting the needed background information,this chapter summarizes the strengths and weaknesses of the various approaches that need to be considered in interpreting the results of the impact analyses. This consideration includes balancing the many limitations that preclude making accurate specific predictions with the need for providing the best available information for conducting a risk-based analysis of the potential consequences of climate change.

CLIMATE AND THE GREENHOUSE EFFECT

The ensemble of weather events at any location defines the climate in that place. The climate is described by such measures as the averages of temperature,precipitation,and soil moisture as well as the magnitude and frequency of their variations,the likelihood of floods and droughts,the temperature of the oceans,and the paths and intensities of the winds and ocean currents. In contrast to climate's focus on average conditions over seasons to centuries and longer, weather describes what is happening at a particular place and time (e.g.,when and where a thunderstorm occurs). Although the weather is constantly changing,the time- and space-averaged conditions making up the climate can also vary from season to season or decade to decade and can change significantly over the course of decades or centuries and beyond. While a slowly warming climate may seem hardly noticeable,the record of the Earth's environmental history indicates that seemingly small changes in climate (e.g., changes in the long-term average temperature of a few degrees) can have quite noticeable consequences for society and the environment.

Many factors determine the Earth's weather and climate,including the intensity of solar radiation,concentrations of atmospheric gases and particles,interactions with the oceans,and the changing character of the land surface. The predominant source of warming is energy received from the Sun in the form of solar radiation. Energy from the Sun enters the top of the atmosphere with an average intensity of about 342 watts per square meter. About 25% of this energy is immediately reflected back to space by clouds,aerosols (micron-sized particles and droplets,including sulfate aerosols),and other gases in the atmosphere;an additional 5% is reflected back to space by the surface,making the overall reflectivity (or albedo) of the Earth about 30%. Of the other 70% of incoming solar radiation, about 20% is absorbed in the atmosphere and the rest is absorbed at the surface. Thus,70% of incoming solar energy is the driving force for weather and climate (Kiehl and Trenberth,1997).

Studies of the Earth's climatic history extending back hundreds of millions of years indicate that there have been global-scale climate changes associated with changes in the factors that affect the Earth's energy balance. Factors that have exerted important influences include changes in:solar irradiance,the Earth's orbit about the Sun,the composition of the atmosphere,the distribution of land and ocean,the extent and type of vegetation,and the thickness and extent of snow and glaciers. Records of global glacial extent derived from ocean sediment cores (e.g.,see Imbrie et al.,1992,1993) and of temperature and atmospheric composition derived from deep ice cores drilled in Greenland and Antarctica (e.g., Petit et al.,1999) provide strong indications of the interactions and associations of these various influences. The Antarctic record (Figure 1), for example,indicates that the atmospheric CO_2 concentration can be changed by up to 100 parts per million by volume (ppmv)[2] as a result of the climate changes that occur due to the glacial-interglacial cycling over the past 420,000 years (Petit et al., 1999). While explanations of the relationships among orbital forcing,atmospheric concentrations of GHGs,and glacial extent are not yet fully quantified,it is clear that the Earth's climate has been dif-

[2] Parts per million by volume (ppmv) is equivalent to the number of molecules of CO_2 to the number of molecules of air, which is made up mostly of nitrogen and oxygen.

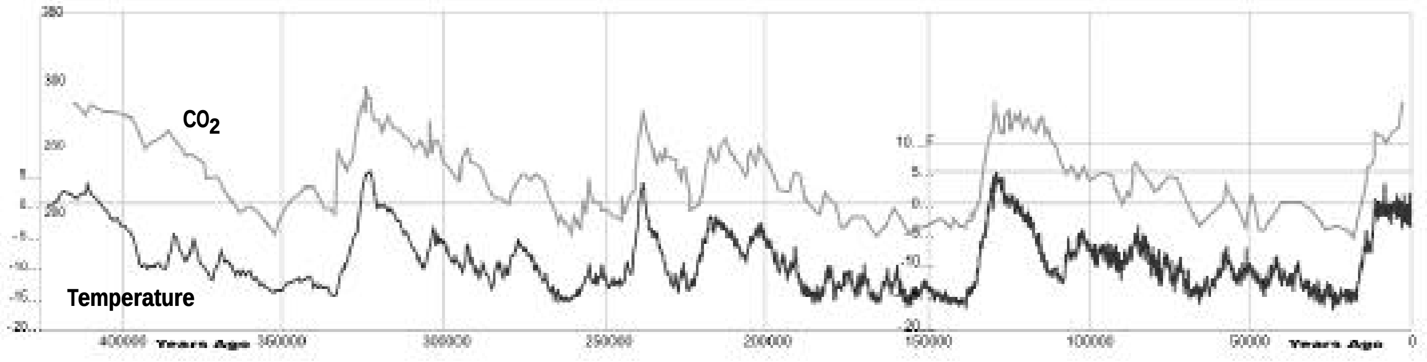
ferent when atmospheric composition has been different. Analyses indicate that these natural changes in atmospheric composition are being driven mainly by the initial changes in climate due to the orbital changes,and are then acting as feedbacks that amplify or moderate the initial changes in the climate. Given the evidence that changes in atmospheric composition have been a factor in determining climatic conditions over the Earth's history, human-induced changes in atmospheric composition (particularly greenhouse gas concentration) would also be expected to have an important influence on the climate. Scientific understanding of the changes in climates of the geological past would be significantly compromised if the Earth's climate were not now responding to changes in atmospheric composition.

Changes in the Earth's orbit around the Sun occur quite slowly, with periods ranging from about 20,000 to 400,000 years (Berger, 1978;Berger and Loutre,1991). While these long periods mean that changes will be slow, their influences are steady and the changes,along with other factors,seem to cause trends in temperature evident in records of a few centuries or more in length (Berger, 1999). On the time scale of many centuries to millennia,observations from Antarctic ice cores (Petit et al.,1999; Imbrie et al.,1989) suggests that these orbital changes cause changes in climate that lead to changes in the amount of carbon dioxide in the atmosphere. These changes in the CO_2 concentration, working in parallel with the dynamics of ice sheets and their underlying geological substrate, then seem likely to have reinforced the glacier-inducing and melting influences of the changes in solar radiation caused by the orbital variations (Pisias and Shackleton,1984;Shackleton et al.,1992; Petit et al.,1999;Clark et al.,1999). Following the end of the last glacial period about 10,000 years ago,orbital changes appear to have contributed to a Northern Hemisphere warming that peaked about 6,000 years ago when the Earth was closer to the Sun during the Northern Hemisphere summer. Subsequent to this peak,a slow and sometimes intermittent cooling of the Northern Hemisphere started that seems to have continued until overwhelmed by the warming effects of the recent increases in the CO_2 concentration due to human activities (Thomson,1995).

The amount of solar radiation reaching a given location on the Earth can also be changed by changes in solar output (irradiance). Satellite observations of solar irradiance over the past 20 years indicate that the amount of energy put out by the Sun varies by about 0.1% over the 11-year sunspot cycle,with more energy coming out at sunspot maximum and less at solar minimum (Willson,1997). Analyses of records of atmospheric conditions indicate that stratospheric temperatures do vary somewhat with

Figure 1: Changes in the global average concentration of carbon dioxide (light) and the local surface air temperature (dark) have been reconstructed for the past 420,000 years using information derived from an ice core drilled at the Vostok station in Antarctica (Petit et al., 1999). The local temperature record is derived from measurements of oxygen-18 isotope concentrations in the water frozen as snow. The record shows a series of long-term variations in the lower tropospheric (above the inversion layer) temperature that are similar to changes in solar radiation caused by changes in the Earth's orbit around the Sun. For most of past 420,000 years, temperatures in Antarctica (and by implication the globe) have been lower than recent values. Independent geological evidence indicates that glacial ice amounts peaked on Northern Hemisphere continents during these cold periods, most recently about 20,000 years ago. The very brief warm periods coincide with interglacial periods over the world's continents, with the Eemian interglacial of about 120,000 years ago being the last warm period until the present interglacial started about 10,000 years ago. In the absence of human influences on the climate, models of the advance and retreat of glaciers that include representations of changes in the Earth's orbit, natural variations in atmospheric composition, effects of climate change on land cover, sinking and rising of land areas due to the presence or absence of glaciers, and other factors suggest that the Earth would not return to glacial conditions for many thousands of years (Berger et al., 1999). These studies also suggest that global-scale glaciation would be unlikely if the CO_2 concentration is above about 400 ppmv.

400,000 Years of Antarctic CO_2 and Temperature Change



the sunspot cycle,but most scientists believe that these variations are too small to have caused a detectable impact on global average surface temperatures,especially with the thermal buffering provided by the global ocean. However, over the longer-term, reconstructions of changes in solar irradiance suggest that there may have been an increase of 0.24% to 0.3% in solar output over the past several centuries (Lean et al.,1995;Hoyt and Schatten, 1993). Calculations indicate that this increase in solar energy may have created a global warming of as much as 0.4˚F (about 0.2˚C) from the 17th to early 20th century, and perhaps contributed to a small cooling influence since solar irradiance peaked near the middle of this century (Lean and Rind,1998). Over hundreds of millions of years, astronomical studies indicate that the amount of solar energy emitted by the Sun has been slowly increasing,but that these changes are too slow to be inducing noticeable climate change during human existence.

For global average temperatures to be relatively stable over time,there must be a balance of incoming solar energy and outgoing energy radiated away as heat (or infrared) energy. Observations from satellites confirm that the amount of outgoing energy is in close balance with the amount of absorbed solar energy. However, the observations of the amount of energy being emitted are consistent with a celestial body (like the Moon) that has an average temperature close to 0˚F (about –18˚C). Were 0˚F really the surface temperature,the Earth's surface would be covered with snow and ice and it would be too cold for life as we know it. Observations indicate,however, that the Earth's atmosphere acts to warm the surface in a manner similar in effect (but different in detail) to the glass panels of a greenhouse. The Earth's natural "greenhouse"effect occurs because only a small fraction of the infrared radiation emitted by the surface and lower atmosphere is able to move directly out to space. Most of this heat radiation is absorbed by gases in the atmosphere and then,along with other contributions of energy to the atmosphere (e.g.,from absorption of solar energy or heat released by the condensation of precipitation) is re-emitted,either out to space or back toward the surface. Because the downward emitted energy is available to further warm the surface,this blanketing effect raises the average surface temperature of the Earth to about 58˚F (about 14˚C) (Jones et al.,1999).

The gases that absorb and reemit infrared radiation are called greenhouse gases (GHGs). The set of GHGs includes water vapor (the most important greenhouse gas),carbon dioxide (the most important greenhouse gas whose concentration is being directly influenced by human activities),methane, nitrous oxide, chlorofluorocarbons,stratospheric and tropospheric ozone,and others. Most of the GHGs occur naturally in the atmosphere,contributing to the natural greenhouse effect that acts to keep the Earth at a higher temperature than it otherwise would be were these gases not present. Observations and laboratory experiments indicate that as the amount of these GHGs is increased,more of the infrared radiation emitted upward from the surface and lower atmosphere is absorbed before being lost out to space. This process intensifies the natural greenhouse effect,trapping more energy near the surface and causing the temperatures of the surface and atmosphere to rise (e.g.,see Goody and Yung,1989).

Small particles or droplets (known collectively as aerosols) and changes in cloudiness and land reflectivity can affect how much energy is absorbed by the Earth,creating a warming influence if the overall reflectivity decreases,or a cooling influence if overall reflectivity increases. For example,aerosols can result from major volcanic eruptions or burning of sulfur-laden coals or vegetation (e.g.,both natural and human-induced fires). Cooling can result when light colored aerosols (such as sulfate aerosols or volcanically injected aerosols) increase the amount of solar energy reflected back to space and thereby decrease the amount of energy absorbed by the atmosphere and surface. In addition to their direct effect,it is possible that sulfate aerosols exert an indirect cooling influence by increasing the reflectivity, extent,and character of clouds. By contrast, carbonaceous aerosols,such as organic compounds and soot that are injected by fires and inefficient combustion can increase solar absorption by the atmosphere,thereby creating a warming influence by adding to the amount of energy that can be recycled by the greenhouse effect. Changes in the vegetation cover can themselves affect the energy balance, changing surface reflectivity, evapotranspiration rates,wind drag,and the amount by which snow cover can increase surface reflectivity in winter (Pitman et al.,1999). Unfortunately, the understanding of these direct and indirect influences is quite limited,although they are not thought to be dominant (IPCC,1996a).

While the large-scale,long-term climate of the Earth as a whole is determined by the balance of incoming solar radiation and outgoing infrared radiation (moderated by the movement of energy within the Earth system),the climate at a particular place depends on interactions of the atmosphere,land surface (including its latitude,altitude,type,and vegetative cover),and oceans. The atmosphere and oceans transport energy from place to place,store it in the upper ocean,transform the form of energy from heat to water vapor through evaporation and back through condensation,and create the climate experienced at particular places. Some of the interactions are very rapid,as in the creation and movement of storms that have important local influences. Others,however, are quite slow, as in the several year cycle of El Niño (warm) and La Niña (cold) events in the tropical eastern and central Pacific Ocean that influence the weather around much of the world. Changes in land cover also cause changes in the amount of energy absorbed or emitted. Such changes can occur as a result of deforestation, changes in snow cover, growth or decay of glaciers,or other factors. Thus, changes in the processes that determine how energy is absorbed,moved around,and stored cause the climate to fluctuate or even change over long periods.

HUMAN ACTIVITIES AND CHANGES IN ATMOSPHERIC COMPOSITION

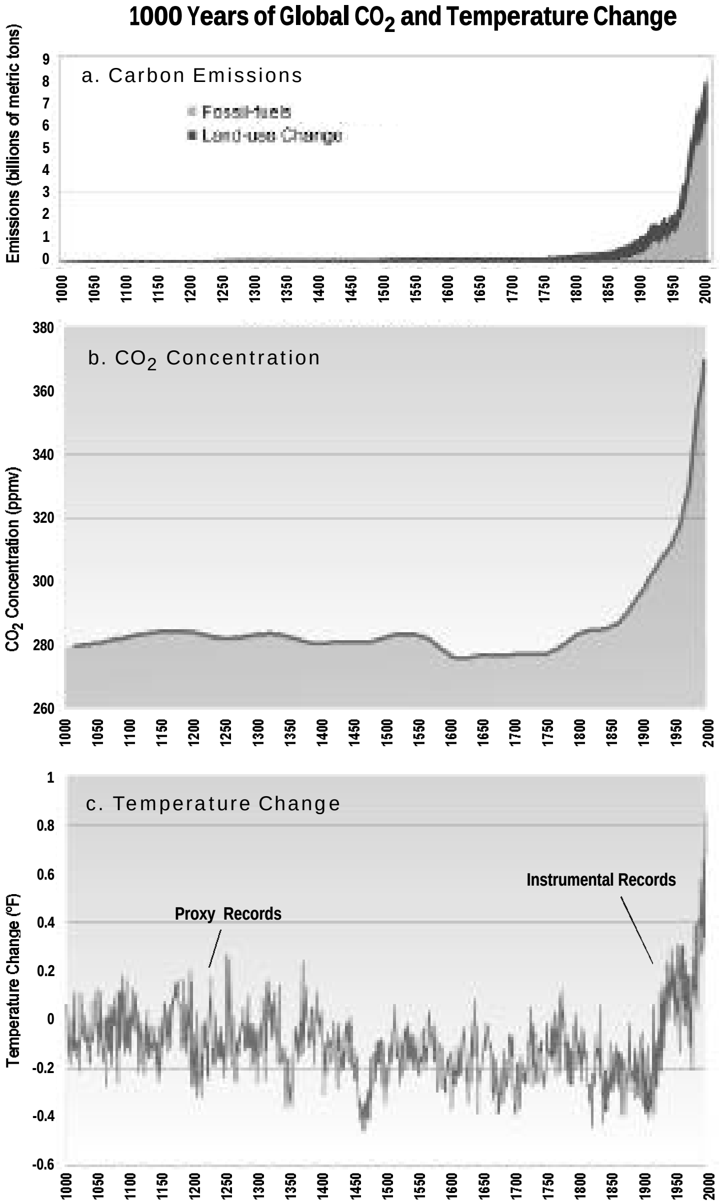
Observations from the Vostok ice core record and other ice core records (e.g., Petit et al.,1999;Neftel et al.,1994) indicate that,until the last couple of centuries,the atmospheric CO_2 concentration had varied between about 265 and 280 ppmv over the past 10,000 years (Indermuehle et al.,1999). Even though the average atmospheric concentration varied over this time by only a few ppmv, exchanges of carbon were occurring among the atmosphere, oceans,and vegetation (each referred to as being a reservoir for carbon,in that carbon comes in and goes out over time). For example,carbon was being taken up by vegetation into living plants and being returned to the atmosphere as soil carbon decayed. Carbon dioxide was also being released into the atmosphere as cold,upwelling ocean waters warmed in low latitudes,and CO_2 was being taken up in the cold waters sinking in high latitudes. Estimates of the annual fluxes (transfers) of carbon between the atmosphere and ocean (and back),and the atmosphere and vegetation (and back),suggest that transfers of 60 to 90 billion metric tons of carbon (abbreviated as GtC, for gigatonnes of carbon) per year have been taking place for each pathway for thousands of years (Schimel et al.,1995). The relatively stable atmospheric concentration of CO_2 in the 10,000 years prior to the start of human contributions suggests that the fluxes tended to be in balance,with the amounts of carbon (or CO_2) in any particular reservoir not changing significantly over time.

Over the past few hundred years, evidence clearly indicates that human activities have started to change the balance. The lower curve in Figure 2 provides the best available reconstruction of carbon emissions to the atmosphere (as CO_2) since about 1750 (Marland et al.,1999). Deforestation and the spread of intensive agriculture initiated a growth in emissions of CO_2 in the mid-18th century that has moved about 130 GtC from the biosphere into the atmosphere (updated from Houghton,1995) since that time. Starting in the 19th century and accelerating in the 20th century, combustion of coal,oil,and natural gas has led to emissions totaling more than 270 GtC (extended from data presented in Andres et al.,2000). These fuels are collectively referred to as fossil fuels because they were formed many millions of years ago from the fossil remains of plants and animals. The effect of combustion of fossil fuels is to add carbon to the atmosphere that has been isolated in geological formations for many millions of years. Combustion of fossil fuels is currently adding more than 6 GtC per year to the atmosphere.

As indicated in the middle curve of Figure 2,the atmospheric concentration of CO_2 has been responding to these additions. The concentrations shown here are derived from air bubbles trapped in ice cores (Neftel et al.,1994) and since 1957 from direct measurements taken at the Mauna Loa Observatory in Hawaii (Keeling and Whorf, 1999; Conway et al.,1994). These observations,and others from around the world,provide convincing evidence that there has been an increase in the atmospheric CO_2 concentration from historical levels of about 270-280 ppmv in the early 19th century to over 365 ppmv at present. Many types of studies confirm that it has been the rise in CO_2 emissions from land clearing and fossil fuel use that have caused the rise in the atmospheric CO_2 concentration over the last 200 years (e.g.,Wigley and Schimel,2000).

Although the natural fluxes of carbon being exchanged each year between the atmosphere and the oceans and between the atmosphere and vegetation are at least 10 times larger than the 6 GtC/yr from fossil fuel emissions,only about half of the fossil fuel carbon can be taken up by the vegetation and oceans. The other half of the atmospheric increase, for reasons that relate to the slow over-

Figure 2: Records of CO_2 emissions, CO_2 concentrations, and Northern Hemisphere average surface temperature for the past 1000 years: (a) Reconstruction of past emissions of CO_2 as a result of land clearing and fossil fuel combustion since about 1750 (in billions of metric tons of carbon per year) [data from CDIAC, 2000; Andres et al., 2000; Marland et al., 1999; Houghton, 1995; Houghton and Hackler, 1995]; (b) Record of the CO_2 concentration for the last 1000 years, derived from measurements of CO_2 concentration in air bubbles in the layered ice cores drilled in Antarctica, a location that has been found to be representative of the global average concentration [data from Etheridge et al., 1998; Keeling and Whorf, 1999]; (c) Reconstruction of annual-average Northern Hemisphere surface air temperatures based on paleoclimatic records (Mann et al., 1999). For the Mann et al. data, the zero change baseline is based on the average conditions over the period 1902-80. The error bars for the estimate of the annual-average anomaly increase somewhat going back in time, with one standard deviation being about 0.25˚F (0.15˚C). Although this record comes mostly from the Northern Hemisphere, it is likely to be a good approximation to the global anomaly based on comparisons of recent patterns of temperature fluctuations. See Color Plate Appendix.



turning rate of the oceans and limits on how much vegetation can accumulate, is destined to remain in the atmosphere for at least 100 years, even if global emissions are substantially reduced. Just as adding water to a multi-pool fountain raises its level even though the amount of water being pumped through is many times larger than the amount of water being added, adding carbon (as CO_2) from geological storage to the amount being exchanged among the atmosphere, ocean, and vegetation reservoirs causes a rise in the atmospheric concentration (as well as in ocean and vegetation levels).

HUMAN ACTIVITIES AND CLIMATE CHANGE

Based on scientific understanding of the greenhouse effect, increasing the atmospheric composition of greenhouse gases should cause the global temperature to rise. The top curve of Figure 2 presents a reconstruction of the annual-average near surface air temperature for the last 1000 years for the Northern Hemisphere (Mann et al., 1999); Crowley (2000) finds similar results. Because instrumental data are sparse or non-existent before the mid-19th century, these estimates of temperature are based on such proxy indicators as widths of tree-rings, types of vegetation, amounts of snowfall as recorded in ice cores, etc. While these measures are not as precise as thermometers, such indicators have proven to be reasonably accurate for reconstructing the fluctuations in Northern Hemisphere average temperature, providing a good indication of the variations that have occurred prior to the start of instrumental data in the mid 19th century. Although not as precise in their time resolution, records of subsurface ground temperatures also confirm that long-term warming is occurring (Huang et al., 2000).

These proxy data suggest that for most of the past 1000 years, the Northern Hemisphere average temperature had been slowly cooling at about –0.03˚C/century (Thomson, 1995; Mann et al., 1999). Then, starting in the late 19th century, the temperature started to rise, and has risen especially sharply during the latter part of the 20th century. This 20th century warming appears to be unprecedented compared to natural variations prior to this century that were presumably caused by solar, volcanic, and other natural influences. In addition, the current warming is much more extensive and intense than the regional scale warming that peaked about 1000 years ago in Europe during what is referred to as the Medieval Warm Period (Mann et al.,1999;Crowley, 2000). The recent warming is also far more than can be characterized as a recovery from the cool conditions centered in Europe and the North Atlantic region a few hundred years ago that are often referred to as the Little Ice Age (Crowley and North,1991;Mann et al.,1999;Crowley, 2000). Overall,looking back over the few thousand years for which we can reconstruct estimates of large-scale temperatures,the current warmth of global conditions appears unprecedented.

Figure 3 presents the instrumental records of temperature change for the globe and for the US. The global results indicate that the annual average temperature has risen about 1.0˚F (about 0.6˚C) since the mid-19th century, with sharp rises early and late in the 20th century and a pause in the warming near the middle of the century. Sixteen of the 17 warmest years this century have occurred since 1980,and,counting the projected temperature for 1999,the seven warmest years in the instrumental record have all occurred in the 1990s. The global average temperature in 1998 set a new record by a wide margin, exceeding that of the previous record year, 1997, by about 0.3˚F (Karl et al.,2000). Higher latitudes have warmed more than regions nearer the equator and nighttime temperatures have warmed more than daytime. To the extent that available data are globally representative,the 1990s are the warmest decade in the last 1000 years (the period for which we have adequate data,see Mann et al., 1999). A recent report by the National Research Council (NRC,2000) confirms that,although satellite-measured temperatures of the lower atmosphere since that record began in 1979 are rising more slowly than surface temperatures,the two measures of the global climate have been rising at similar rates over the four-decade long record of balloon measurements (Angell,2000). The NRC report also confirms that there is good reason to accept the evidence that the increase in the surface temperatures is real and has become relatively rapid compared to the rates of warming earlier in the 20th century.

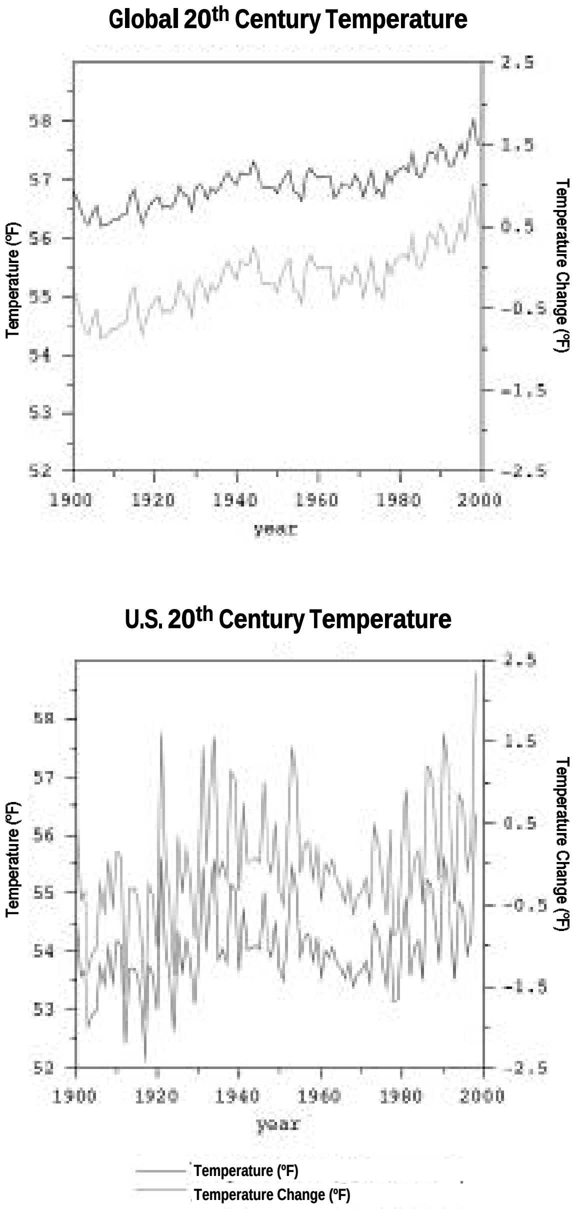


Figure 3: (a) Global annual-average surface temperature and temperature change for combined land and ocean regions for the period 1900-1999 based on the method of Quayle et al. (1999); (b) US annual-average surface temperature and temperature change for the period 1900-1999 using the USHCN data set (Easterling et al., 1996). See Color Plate Appendix.

Of course,distributions of temperature change around the world are more varied,with some regions warming at a rate substantially greater than the global average and others even experiencing a modest cooling. Observations derived from the United States Historical Climatology Network (USHCN) for 1200 of the highest quality observing stations in the US indicate that surface temperatures have increased over the past century at near to the global average rate. As is the case around the world,the largest observed warming across the US has occurred in winter. Note that it is generally not appropriate to compare the spatial patterns of the satellite observations with the spatial patterns of the surface temperature record because, for example,the atmosphere redistributes temperature anomalies,near surface inversions disconnect surface and atmospheric temperature changes,and forcings such as by volcanic eruptions and ozone changes have different effects on the surface and atmospheric temperature trends. However, other measures of climate change across the US indicate that changes are indeed occurring.

An increasing number of studies indicates that the time histories of greenhouse gas emissions,concentrations,and surface temperature are closely related rather than just random correlations (IPCC 1996a; Tett et al.,1999). Each type of factor that could contribute to the observed warming of the climate would have a distinctive character or "fingerprint" that can be searched for in the observations. For example,an increase in solar radiation would be expected to warm both the lower and upper atmosphere, yet the lower atmosphere has warmed while the upper atmosphere has cooled. Although there is some evidence that some of the warming in the first half of the 20th century may have been due to an increase in the intensity of solar radiation,major warmings like that of the 20th century have not been evident in the records of the past thousand years (and likely much longer),suggesting that an increase in solar radiation is unlikely to be the primary cause of the recent warming (IPCC,1996a).

It is also becoming more clear that the change is not due to a diminution of the influence of major volcanic eruptions,especially because the relatively recent El Chichón (in 1983) and Pinatubo (in 1991) eruptions injected very large amounts of aerosol into the stratosphere and yet,although there was some cooling,global average temperatures remained well above temperatures following the Krakatoa eruption in 1883 and major eruptions during the first decade of the 20th century (see Figure 3). Third, were the warming due mainly to a change in the coupling of the atmosphere and oceans, we would expect to see variations of this size and rate in the past. However, such variations do not appear to have occurred, except perhaps as the world was emerging from the last glacial period when large ice sheets were melting. Lastly, the possibility of urban heating contaminating the temperature record has been examined in numerous studies and in each case only about 0.1˚C or less of the observed 0.6˚C warming over the 20th century can be linked to urban contamination of temperature records (Karl et al.,1988, Jones et al. 1990,Easterling et al.,1997). Based on the inadequacy of natural factors to explain the recent change, the IPCC (1996a) concluded that

> "the probability is very low that these correspondences [i.e.,the observed time history of the geographical,seasonal and vertical patterns of atmospheric temperature change] could occur by chance as a result of natural internal variability only. The vertical patterns of change [i.e.,with stratospheric cooling and tropospheric and surface warming] are also inconsistent with those expected for solar and volcanic forcing."

More recent studies are confirming these findings (e.g.,see Hegerl et al.,1997;Barnett et al.,1999; Knutson et al.,1999).

Climatic changes due to factors being influenced by human activities also have characteristic fingerprints. Because greenhouse gases are essentially transparent to solar radiation, yet absorb infrared radiation,increasing the concentrations of greenhouse gases creates a warming influence at the surface and a cooling influence in the stratosphere (which is consistent with what has been occurring). Increases in sulfate aerosols that have occurred over the 20th century as a result of sulfur dioxide emissions resulting from coal combustion would be expected to have led to a surface cooling that would be greater in the Northern Hemisphere than in the Southern Hemisphere and most dominant in the mid-20th century. Depletion of stratospheric ozone as a result of the emissions of chlorofluorocarbons would be expected to have led to surface warming and cooling of the lower stratosphere.

Accounting for the effects of the increases in greenhouse gas and aerosol concentrations and the changes in stratospheric ozone,the time and space patterns of temperature changes are consistent with a strong warming during the 20th century caused by the changes in greenhouse gas concentrations and a cooling influence due to aerosols that grew in strength in the middle of the 20th century. Based on these diverse results,the IPCC (1996a) concluded that "the balance of evidence suggests a discernible human influence on global climate." Since that assessment,an increasing number of studies are providing more quantitative information indicating that the 20th century warming is unlikely to be due to solely to changes in solar radiation and is likely to be a result of the increasing concentrations of greenhouse gases and aerosols,especially during the latter half of the 20th century (Tett et al.,1999;Stott et al.2000).

APPROACHES FOR ASSESSING THE IMPACTS OF CLIMATE CHANGE

Because it would be very disruptive to rapidly terminate use of fossil fuels around the world[3], it is clear that the atmospheric CO_2 concentration will continue to increase for many decades into the future. In addition,the concentrations of other greenhouse gases are increasing,and limitation of emissions of these gases would require implementing significant emission control measures. Theoretical analyses, measurements in laboratory and field experiments, and knowledge of the processes determining the temperatures of the Earth, Mars, and Venus all indicate that increasing the concentrations of GHGs in the atmosphere will increase the natural greenhouse effect, causing the world to warm. Given the weight of evidence provided by assessments of the potential for climate change, prudent risk management demands an assessment of the potential impacts of climate changes that will occur over the 21st century.

Early attempts to investigate the potential consequences of climate change often simply assumed that climate would change by an arbitrary amount (e.g., temperatures increase by 5°F, or precipitation goes up or down by 20%). For other studies (e.g., USEPA, 1989), results from model simulations with a doubled CO_2 concentration were all that were available. Such studies, however, could only be used to investigate the potential sensitivity of existing systems to a different climate, rather than to explore how such changes might evolve over time and in so doing how these changes might spur natural and societal adaptations that could moderate the potential consequences.

In this Assessment, our goal is to examine the consequences of time-dependent climatic change. Doing this requires a two-step process. First, estimates of how the climate may change in the future must be developed. The development of scenarios of climate change that can be used in this effort is the primary subject of this chapter. Second, estimates must be developed of how the climate will affect the environment and society, and of how society might respond. These topics are the subject of subsequent chapters, but are coupled to this chapter in that the potential impacts often depend on having certain types of information available about how the weather or climate will change. To assist in these analyses, this chapter summarizes our understanding about a number of the particular climatic influences that may occur.

Three approaches have been used to develop the information base needed to evaluate the potential consequences of climate change on the US:

- Carefully checked historical data are being used to examine the potential consequences of the continuation of past climatic trends and weather and climate extremes in order to evaluate the consequences of recurrences of the types of climate fluctuations and variations that occurred in the past (e.g., the Dust Bowl period);
- Results from general circulation model simulations extending out to the year 2100 are being used to generate plausible quantitative estimates of the combined influences on climate of projected changes in greenhouse gas and aerosol concentrations; and
- Sensitivity analyses are being encouraged to facilitate exploration of the limits of vulnerability (both strengths and weaknesses) for particular regions, sectors, societal activities, and ecosystems.

This strategy has several advantages in that it serves multiple purposes and addresses several needs. These include: (a) providing a historical basis for assessing the significance of potential changes in the climate; (b) providing a range of plausible future climatic conditions as a means of recognizing the limitations and degree of uncertainty in the model formulations or assumptions; (c) incorporating the range and character of natural variability for consideration, given its importance for human and natural systems; (d) providing opportunities to compare model simulations with observations in order to evaluate model capability; and (e) ensuring opportunities to include sensitivity analyses to explore the implications of thresholds or limits in human and ecosystem adaptability. While not all groups have been able to pursue all approaches fully, having a variety of approaches has helped broaden the approach and served many of these purposes.

Thus, in this multi-pronged approach, climate models provide the Assessment process with physically consistent projections that are sufficiently plausible and quantitative to investigate the potential impacts of climate change on water, health, ecosystems, food production, and coastal areas, among other types of consequences. Use of the model projections is guided by knowledge of the climate of the last century and sensitivity analyses, and experience with the weather and climate during the historical record provides a benchmark, a personal and national context for assessing the future.

[3] Estimates are that it would take a reduction in cumulative emissions of somewhat over 50% during the 21st century to stop any further rise in CO_2 concentration, with virtually no emissions allowed thereafter. Even stabilizing the atmospheric concentration at twice its preindustrial level would require limiting average emissions over the 21st century to about 130% of current levels, as opposed to the projected tripling of CO_2 emissions by the year 2100 as projected by the mid-range emissions scenario (IPCC, 1996a).

1. Use of Historical Records[4]

Records of how the climate has actually changed over the past century and over earlier times provide an important context for evaluating the potential consequences of future changes in climate. Climatologists have used two types of data to identify changes and variations in climate. The first consists of actual observations made over the 20th century of temperature,precipitation,and other weather-related variables that have been routinely measured at thousands of locations across much of the globe,including the US. These data have been supplemented over the past few decades by space-based measurements. Because the observing methods,instruments,and station locations have changed over time, climatologists have used various methods to assess and correct for the non-climate related factors that can affect these data.The second type is "paleoclimate"data:physical,biological,and chemical indicators recorded in rocks,ice,trees,and sediments that can be used to infer past climate conditions. Examples include the width or density of tree rings,ice cores containing air that has been trapped inside the ice for thousands and even hundreds of thousands of years,sediment at the bottom of lakes and the ocean,and others. These data are calibrated against modern-day climate measurements,and indicate that,on a global scale, climate fluctuations have been at most several tenths of a degree F (few tenths of a degree C) over the past several thousand years,indicating a quite stable climate compared to conditions occurring over the past million years.

For the US,carefully documented data records exist for the 20th century that provide climate information for most of the inhabited areas of the country. Data from the United States Historical Climatology Network (USHCN),which has been developed from a carefully selected and processed set of observations from the US Cooperative Observing Network, have been thoroughly quality controlled (Easterling et al.,1996). The data set was developed and is maintained by NOAA's National Climatic Data Center (NCDC). It contains monthly averaged maximum,minimum,and mean temperature and total precipitation data for 1200 of the highest quality observing stations in the continental United States for the period 1895 to 1997. These data have been carefully screened for recording errors and,based on well-defined procedures,adjusted for long-term variability or trends that might be introduced by changes in instrumentation,station location,urban warming,or other factors that can cause small,but important,contamination of temperature and precipitation observations. A similar high-quality data set has been developed for Alaska,but the spatial representativeness of these data sets is not as high due to the sparsity of stations.

In addition to the monthly average station data,data sets of daily maximum and minimum temperature and precipitation have been used to examine variability and trends in climatic parameters. The Daily Historical Climatology Network data set contains observations for 187 high-quality stations in the contiguous US for the period 1910-1997 and observations for 1000 stations in the contiguous US for the period 1948-1997. An additional data set ("Probabilities of Temperature Extremes in the U.S.A." CD-ROM, available from NCDC) has been developed that includes observations of daily maximum and minimum temperatures for 300 stations in the contiguous US,Alaska,and Hawaii for the period 1948-1996. The software on this CD-ROM uses a statistical model described in Karl and Knight (1997) to provide probability estimates of how daily extreme temperatures and heat waves may change under various warming scenarios. This CD-ROM also contains software to allow the user to examine probabilities of extreme daily temperatures under the observed climate and how they might change with climate change.

An important additional data set for sensitivity studies in examining ecosystem impacts has been provided by the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP Members,1995;Kittel et al.,1995,1997). The VEMAP data set extends from 1895-1993. This record was created by using statistical models that could link data from long-term stations to help fill in records at stations spanning only part of the period 1895-1993. The statistical methods allowed information for missing periods to be inferred and provided a spatially and temporally uniform data set for driving ecosystem and agricultural models, for example. The VEMAP record is based on USHCN stations plus USDA-Natural Resources Conservation Service Sno-Tel stations for high elevation precipitation. Altogether, the data set draws on information from about 8000 stations. The processing algorithm for deriving a high spatial resolution data set accounts for elevation and slope changes. The primary data set provides gridded monthly average data for minimum and maximum temperature, precipitation,humidity (both relative and absolute) and solar radiation at a 0.5° x 0.5° latitude-longitude spacing (about 27 miles or 43 kilometers in longitude and 35 miles or 55 km in latitude). Because some ecosystem and agricultural models require

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[4] The data sets described in this section are available at http://www.nacc.usgcrp.gov/scenarios/

estimates of daily projections of these variables, a statistically based "weather-generator" technique has been used to provide estimates of daily temperature and precipitation for each grid location.

2. Use of Climate Model Simulations[5]

As a second approach, physically consistent projections of future climatic conditions derived from climate models provide an important tool for investigating the potential consequences of climate change. Climate models have been developed and are used because the Earth's atmosphere/ocean/land/ice system is far too complex to reproduce in a laboratory and simple extrapolations of past changes in climate cannot account for the rapid changes in human influences on the climate. These mathematical representations of the Earth atmosphere/ocean/land/ice system rely on the well-established laws for conservation of mass, momentum, and energy, and on empirical relationships derived from observations of how particular processes work, to specify transfers of these conserved quantities among latitude/longitude/altitude grid boxes that cover the Earth like tiles. The typical size of the grid boxes that cover the Earth in current atmospheric models is about the size of a modest sized US state and these boxes average several thousand feet (about a kilometer) thick; ocean models tend to have finer grid sizes to represent the smaller ocean eddies.

Developing models that can be used to project possible future climatic conditions requires incorporating the most important physical principles and processes that determine climatic conditions. The most comprehensive models of Earth's climate system to date are called General Circulation Models or GCMs[6] (e.g., see Nihoul, 1985; Washington and Parkinson, 1986; Mote and O'Neil, 2000). The domains for these models include the global atmosphere (up to mid-stratospheric altitudes), the oceans (from surface to the bottom), the land surface (although with limited detail in mountainous regions), and sea ice and snow cover (with Greenland and Antarctic ice caps assumed to be present). The processes represented include solar and infrared radiation, transfer and transformation of energy, evaporation and precipitation, winds and ocean currents, snow cover and sea ice, and much more. While full detail cannot always be included, present models are constructed so as to represent key processes with sufficient detail that the large-scale climate and its sensitivity to potential changes by human activities can be self-consistently calculated. Tests are performed to determine the ability of the models to simulate the evolution of temperature, rainfall, snow cover, winds, soil moisture, sea ice, ocean circulation, and other key variables over the entire globe through the seasons and over periods of decades to centuries (e.g., Gates et al., 1999; Meehl et al., 2000a).

The advantages of using model simulations are that they are quantitative and are based on the fundamental laws of physics and chemistry, often affected and moderated by biological interactions. However, while attempts are made to ensure climate models are adequately comprehensive, such models are obviously simplified versions of the real Earth that, in their current versions, cannot capture its full complexity, especially at regional and smaller scales. The level of confidence that can be placed in such models can be evaluated by testing their ability to simulate past and present climate conditions. Among the tests that have been used to evaluate the skill of climate models have been comparisons of model simulations of the weather (to the limit that it is predictable), the cycle of the seasons, climatic variations over the past 20 years when globally complete data sets are available, climatic changes over the past 150 years during which the world has warmed, and climatic conditions for periods in the geological past when the climate was quite different than at present. Studies on comparisons of model simulations of paleoclimatic variations also suggest that models can simulate some of the types of changes that have been reconstructed from the geological records (e.g., COHMAP, 1988; Kutzbach et al., 1993; Joussaume et al., 1999). Beyond studies of particular periods, only quite simplified models have been able to be tested on their simulations of the onset, duration, and termination of the glacial periods of the past million years, and these results suggest that the GCMs likely do not adequately include all of the feedback processes that may be important in determining the long-term climate (Berger, 1999; Berger et al., 1999).

The capabilities of the most developed of these models have been carefully reviewed by the IPCC and as part of other national and international scientific efforts to evaluate their ability to represent

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[5] Results from the models described in this section are available at http://www.nacc.usgcrp.gov/scenarios/

[6] Some studies refer to these models of the global climate system as Global Climate Models (also condensed to GCMs). However, technically, it is only the atmospheric and oceanic components of such models that are actually considered to be General Circulation Models in that they calculate how air and oceans move. Because the atmospheric and oceanic parts of global climate models are so dominant and so widely discussed, we have chosen to refer to the overall climate system models as General Circulation Models.

most aspects of the present and historical climates (e.g.,see discussions in IPCC,1996a;Gates et al., 1999;Meehl et al.,2000a). These evaluations indicate that climate models represent many, but not all, of the important large-scale aspects of the global climate quite well. The evaluations also show, however, that there are important limitations of their simulations of regional conditions,particularly in and downwind of mountainous regions,because important local influences are not well represented in the models. Model capabilities for representing natural climate variations over periods of years (e.g.,the El Niño/La Niña fluctuations) to several decades (e.g., over the Pacific and Atlantic oceans) are only beginning to show success. Basically, the model evaluations indicate that the models can be used to provide important and useful information about potential long-term climate changes over periods of up to a few centuries on hemispheric scales and across the US,but care must be taken in interpreting regionally specific and short-term aspects of the model simulations. Rather than repeat the full analysis of model results being undertaken as part of the ongoing IPCC assessments,this chapter focuses on the performance of the two selected models over the US,while the Assessment as a whole focuses on determining how the selected climate change scenarios may impact human and natural systems.

Because these models are based on quantitative, physically based relationships governing,to the extent of current understanding,the global distributions of air pressure,heat,moisture,and momentum, climate models can be used to investigate how a change in greenhouse gas concentrations,or a volcanic eruption,may modify the Earth's climate. Using models in this way enables the generation of information that can potentially be used in assessment of impacts across the regions and sectors of the country. Because of continual efforts at improvement over the last several decades,these models provide a state-of-the-science glimpse into the climate of the 21st century and represent a growing capability to learn how climate change may impact the nation. However, real uncertainty remains in the ability of models to simulate many aspects of the future climate such that the model results must be viewed as providing a view of future climate that is physically consistent and plausible, but incomplete.

To convey the importance of the limitations, assumptions,and uncertainties in the model results, the IPCC has adopted the terms "projection"and "scenario" rather than "prediction"or "forecast"to refer to the results of climate model simulations of the future. This choice is meant to emphasize that we must recognize that climate model simulations do not provide precise forecasts,but rather are best used to develop insights about plausible climate changes resulting from specific assumptions such as about how energy technologies and emissions will evolve. Relying on this approach, even with the recognized uncertainties,can be useful,just as it is in other cases where individuals and organizations make use of information, even if it is associated with some level of uncertainty. For example,many people plan their days around weather forecasts with uncertainty conveyed both in words and numbers,e.g.,a 30% chance of rain,or snow likely with a probability of 70%,etc. Others invest financial resources based on economic trends or decide to purchase a new home based on interest rate analyses. Understood in this light,the model-based scenarios can help to provide useful insights about the consequences of climate variability on the US,but the model results should be considered as plausible projections rather than specific predictions.

3. Use of Vulnerability Analyses

The third approach to exploring potential impacts of future climate change is to ask what degree of change would cause significant impacts in areas of critical human concern,and then to seek to determine the likelihood that such changes might occur (based on the historical record,model simulations, etc.). This approach is a form of "sensitivity analysis"conducted to determine under what conditions and to what degree a system might be sensitive to change. Such analyses are not predictions that such changes will occur; rather, they examine what the implications would be if the specified changes did occur.

For example,questions that might be explored could include:What would happen to weather conditions over the US if El Niño conditions occurred more frequently or more intensely? What would be the implications if there were simultaneous droughts in the US and in other grain-growing regions? What if the 1980s California drought lasted ten years instead of six? What if the deepwater circulation of the North Atlantic Ocean were disrupted and colder conditions prevailed from New England across to Europe? Alternatively, such questions could be phrased:How large would climate change have to be in order to cause a particular impact? How dry would conditions need to be for fire frequency and extent to increase significantly in the southeastern US? How high do ocean temperatures have to become for coral reefs to be seriously threatened? How low does river flow in the Mississippi-Missouri basin have to become for extensive areas of hypoxia (lack of oxygen) to occur in the Gulf of Mexico?

While there are always values for which one could get disastrous consequences,this approach is most useful when it focuses on basing the questions on types of climatic fluctuations, changes, or conditions that might have occurred before the instrumental record began. For example,a recent study by Woodhouse and Overpeck (1998) suggests that the 1930s drought in the Great Plains,while severe, was much shorter than earlier droughts that have occurred in the past several hundred years. They also found that droughts of similar magnitude to the 1930s drought are expected to occur about once or twice a century. Thus,a return of the 1930s drought,perhaps even lengthened,seems a plausible scenario for the future (Stahle et al.,2000 report similar findings). Similarly, various proxy records indicate that droughts in California have lasted much longer than the 1980s drought. The fact that such conditions have occurred suggests that they could occur again,and that it would be prudent to think about the impacts such climate fluctuations might have, given the way society has developed.

Because generating scenarios for sensitivity analyses necessarily focuses on considering particular conditions in particular places inducing particular types of impacts,the details of this approach are not developed in this chapter. Instead,the region and sector chapters pose the questions and contain the information underpinning these analyses and their application.This chapter is instead devoted to building the base of national-scale information that these studies have used.

TRENDS IN CLIMATE OVER THE US DURING THE 20th CENTURY

The climate of the United States contains an incredible variety of climatic types. It ranges from the high latitude Arctic climate found in northern Alaska,to tropical climates in Hawaii,the Pacific Islands and Caribbean,with just about every climate regime in between. Because of this wide array of climate,and the large area involved,the interannual variations (year-to-year variability) of climate in different parts of the country are affected differently by a variety of external forcing factors. Perhaps the most well-known of these factors is the El Niño-Southern Oscillation (ENSO) which has an irregular period of about 2-7 years. ENSO has reasonably well-known effects in different parts of the country. In the El Niño phase,which involves unusually high sea surface temperatures (SSTs) in the eastern and central equatorial Pacific from the coast of Peru westward to near the international date line,effects include more winter-time precipitation in the southwestern and southeastern US,and above average temperatures in the Midwest that,with a strong El Niño,can extend into the northern Great Plains. The La Niña phase,which involves unusually low SSTs off the west coast of South America,often leads to higher winter-time temperatures in the southern half of the US,with more hurricanes in the Atlantic and more tornadoes in the Ohio and Tennessee valleys (Bove et al.,1998;Bove,personal communication). Furthermore,in the summertime,La Niña conditions may contribute to the occurrence of drought in the eastern half of the country (Trenberth and Branstator, 1992).

Other factors that affect the interannual variability of the US climate include the Pacific Decadal Oscillation (PDO),and the North Atlantic Oscillation (NAO). The PDO is a phenomenon similar to ENSO, but is manifest in the SSTs of the North Pacific Ocean (Mantua et al.,1997). The PDO has an irregular period 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,SSTs are higher than normal in the equatorial Pacific,and lower than normal in the northern Pacific,leading to a deepening of the Aleutian Low, higher winter temperatures in the Pacific Northwest,and relatively high SSTs along the Pacific coast. This condition also leads to dry winters in the Pacific Northwest,and wetter conditions both north and south of there. Essentially, the opposite conditions occur in 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 US such that when Greenland is warmer than normal,the eastern US is usually colder, particularly in winter, and vice versa (Van Loon and Rogers,1978).

As context for evaluating the importance of climate change during the 21st century, it is useful to review how the climate over the US has changed over the 20th century. Whereas Figure 3b showed the results for the US as a whole, Figure 4a displays the spatial pattern of the trend in annual average temperature across the US for the past 100 years calculated using the USHCN data set. Over most areas of the US, except for the Southeast,there has been warming of

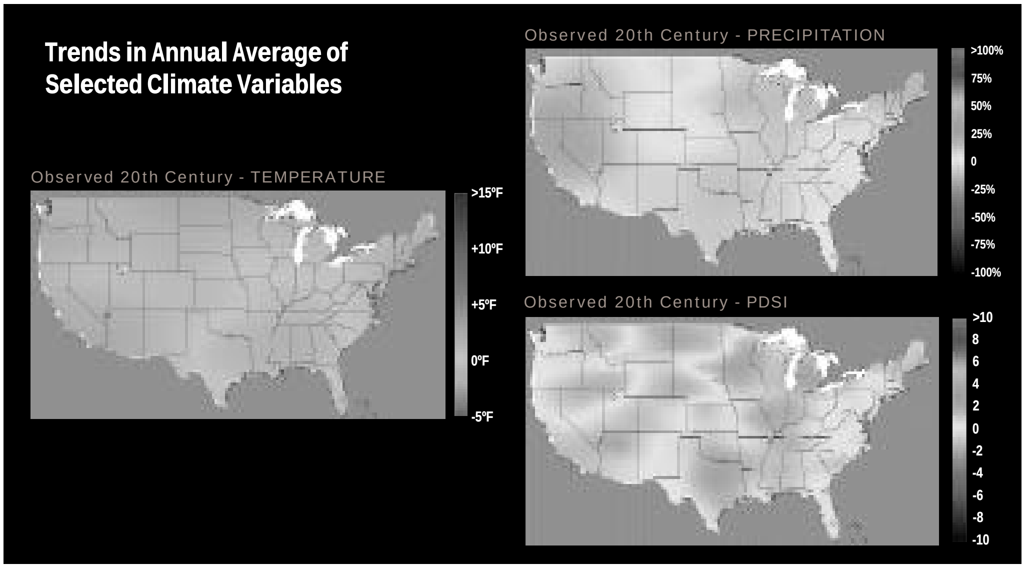


Figure 4: Trends in the annual average of selected climatic variables over the US during the 20th century as derived from observations compiled in the USHCN data set (Easterling et al., 1996). (a) Temperature (˚F/century); (b) Precipitation (percent change/century); (c) Palmer Drought Severity Index (percent change/century). See Color Plate Appendix.

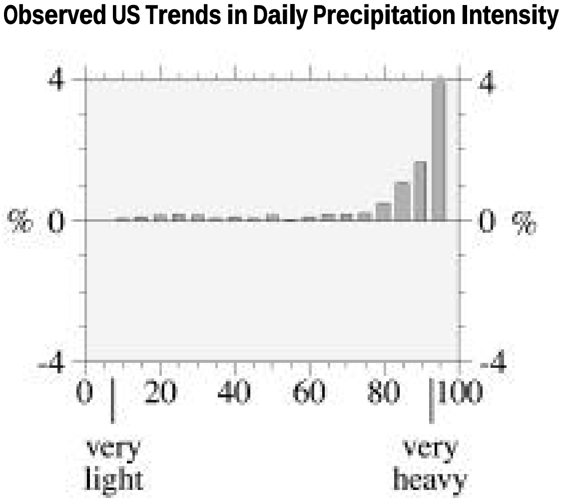


Figure 5: US trends (1910-1996) in mean precipitation (in percent change per century) for various categories of daily precipitation intensity. Values are plotted for each 5%, such that 5 represents from the lowest to 5th percentile and 95 represents the 95th to highest values of precipitation intensity. The lowest to 5th percentile are the lightest daily precipitation amounts and the 95th to highest are the heaviest daily amounts (Karl and Knight, 1998).

more than 1˚F, which is consistent with the observed warming of the world as a whole (Karl et al., 1996). In some regions, particularly in the Northeast, the Southwest, and the upper Midwest, the warming has been greater, in some places such as the northern Great Plains, reaching as much as 3˚F. Warming in interior Alaska has also been quite strong. The Southeast is one of the handful of places in the world indicating some cooling, due perhaps to the increased presence of sulfate aerosols, changes in atmospheric circulation regimes, and/or changes in cloud cover (Karl et al., 1996). Locally in some areas, interannual variability is high enough and trends small enough that some trends are not statistically significant. However, wherever the absence of statistically significant results occurs, significant trends are found nearby, reinforcing the overall observed pattern of warming for the US.

Not only are average temperatures changing, but the variability of the global climate also seems to be changing. For example, Parker et al. (1994) compared spatially averaged variances of annual temperature anomalies between the two periods 1954-1973 and 1974-1993. An increase in temperature variability of between 4 and 11% was found for the latter period. In some areas, such as North America, the increase was even larger. However, Karl et al. (1995a) analyzed changes in variability over the 20th century on a variety of time scales, from 1-day to 1-year for most of the Northern Hemisphere. They found evidence of a decrease in variability on shorter time scales (e.g., 1-day), but no broad scale patterns for longer scale variability. Thus, it appears that, for example, temperature variability on longer time scales (e.g., year-to-year variability) is increasing, but variability on shorter time scales (e.g., day-to-day or month-to-month variability) is decreasing.

Recent analysis of changes in the number of days where the minimum temperature drops below freezing indicates that the frequency of such conditions is changing across the US. Over the 20th century, averaged over the country, there has been a decline of about two days per year (i.e., -2 days/100 years). The spatial pattern of the change mirrors the changes in average annual temperature, showing cooling in the southeastern US and warming everywhere else. Thus, the Southeast has experienced an increase in the number of days below freezing while the western portion of the country has experienced strong decreases, with moderate declines or no change elsewhere. Seasonally, this change is most apparent in winter and spring, with little change in the autumn. Examination of changes in the dates of the first autumn frost and the last spring frost shows a similar pattern, with little change in autumn, but a change to earlier dates of the last spring frost. This shift has resulted in a lengthening of the frost-free season over the country with a trend of 1.1 days per decade (Easterling, 2000).

Observations indicate that total annual precipitation is increasing for both the globe and over the US. Although global precipitation has only increased by about 1%, the increase north of 30˚N has been significantly larger, estimated to be 7-12% (IPCC, 1996a). For the conterminous US, the increase in precipitation during the 20th century is estimated to be 5-10% (Karl and Knight, 1998), which is broadly consistent with the global-scale changes in mid-latitudes. Although there is more spatial variation across the US for precipitation trends than for temperature trends, and although the high year-to-year variability means that small changes are not as likely to be statistically significant, there is an overall increasing trend that is highly significant, both statistically and practically (see Figure 4b). Across the US, most regions have experienced increased precipitation with the exception of localized decreases in the upper Great Plains, the Rocky Mountains, and parts of Alaska. Recent analyses suggest that much of this increase in precipitation is due to increases in heavier precipitation events (see Figure 5) and an increase in the number of rain-days (Karl and Knight, 1998). Not only is this trend evident in daily (24-hour) precipitation events, but the frequency of heavy multi-day (7-day) precipitation events is also increasing (Kunkel et al., 1999). Trends in additional types of variability and extreme events are only starting to become available (Smith, 1999; Easterling et al., 2000a).

Soil moisture is a function of how much precipitation falls and when, as well as how much evaporation and runoff occur. Figure 4c shows the trends in soil moisture across the US during the 20th century, calculated using a Palmer Drought Severity Index model (Palmer, 1965). Overall, there has been relatively little change, except for some areas of the Rocky Mountains and northern Great Plains that have become somewhat drier, and for the Mississippi River Valley, which, the way this index is calculated, tends to show a recovery from the drought years of the 1930s.

CLIMATE MODEL SIMULATIONS USED IN THE NATIONAL ASSESSMENT

Over the past decade, models have been developed that can quite reasonably simulate the climatic conditions of the 20th century and that can be used to simulate the climatic effects of changes in atmospheric composition in the 21st century. These models offer simulations of time-dependent scenarios, based on quantitative relationships, grounded in observational evidence and theoretical understanding. Around the world, there are more than two dozen groups that are developing models to simulate the climate (Gates et al., 1999; Meehl et al., 2000a). However, the various models are in various stages of development and validation, and their treatments of greenhouse gases, aerosols, and other natural and human-induced forcings continue to evolve. The various models that have been used to simulate the climate of the 21st century have been used in various types of simulations, including equilibrium and time-dependent simulations (IPCC, 1996a). The most important characteristics of the models that were considered as possible choices for use in the National Assessment are summarized in Table 1.

For the purposes of the National Assessment, to ensure use of up-to-date results, and to promote a helpful degree of consistency across the broad number of research teams participating in this activity, the National Assessment Synthesis Team (NAST) developed a set of guidelines to aid in narrowing the set of simulations to be considered for use by the regional and sector teams. To build the basis for its set of guidelines, the NAST developed a set of objectives for the characteristics of model simulations that would be most desirable. The criteria for making the selections, which included aspects concerning the structure of the model, the character of the simulations, and the availability of the needed results, included that the models must, to the greatest extent possible:

- be coupled atmosphere-ocean general circulation models that include comprehensive representations of the atmosphere, oceans, and land surface, and the key feedbacks affecting the simulation of climate and climate change;
- simulate the evolution of the climate through time from at least as early as the start of the detailed historical record in 1900 to at least as far as into the future as the year 2100 based on a

well-documented scenario for changes in atmospheric composition that takes into account time-dependent changes in greenhouse gas and aerosol concentrations (equilibrium simulations assuming a CO_2 doubling were excluded) [7];
- provide the highest practicable spatial and temporal resolution (roughly 200 miles [about 300 km] in longitude and 175 to 300 miles [about 275 to 425 km] in latitude over the central US);
- include the diurnal cycle of solar radiation in order to provide estimates of changes in minimum and maximum temperature and to be able to represent the development of summertime convective rainfall;
- be capable,to the extent possible,of representing significant aspects of climate variations such as the El Niño-Southern Oscillation cycle;
- have completed their simulations in time to be processed for use in impact models and to be used in analyses by groups participating in the National Assessment;

Table 1: Characteristics of Global Models

Model Component or Feature	Characteristics of Climate Models Recommended for Use in the National Assessment		Characteristics of Climate Models for which Some Results Were Available for the National Assessment				
	Canadian Climate Centre (CGCM1)	Hadley Centre, United Kingdom (HadCM2)	Max Planck Institute, Germany (ECHAM4/ OPYC3)	Geophysical Fluid Dynamics Laboratory (GFDL)	National Center for Atmospheric Research (NCAR CSM)	Parallel Climate Model (PCM)	Hadley Centre, United Kingdom (HadCM3)
Atmospheric resolution in horizontal (latitude-longitude) and vertical	3.75° by 3.75° (spectral T32) 10 layers	2.5° by 3.75° (grid) 19 layers	2.8° by 2.8° (spectral T42) 19 layers	3.75° by 2.25° (spectral R30) 14 layers	2.8° by 2.8° (spectral T42) 18 layers	2.8° by 2.8° (spectral T42) 18 layers	2.5° by 3.75° (grid) 19 layers
Treatment of land surface, evaporation and evapotranspiration	Modified bucket for soil moisture	Soil layers, plant canopy, and leaf stomatal resistance included	Soil layers, plant canopy, and leaf stomatal resistance included	Simplified bucket for soil moisture	Soil layers, plant canopy, and leaf stomatal resistance included	Soil layers, plant canopy, and leaf stomatal resistance included	Soil layers, plant canopy, stomatal resistance,and CO_2 processes included
Includes diurnal cycle	Yes	Yes	Yes	No	Yes	Yes	Yes
Oceanic resolution in horizontal (latitude-longitude) and vertical	1.8° by 1.8° 29 layers (based on GFDL MOM 1.1)	2.5° by 3.75° 20 layers	2.8° by 2.8° 9 layers	1.875° by 2.25° 18 layers (GFDL MOM 1.1)	2.4° by 1.2° (variable) 45 layers	0.66° by 0.66° (variable) 32 layers	1.25° by 1.25° 20 layers
Treatment of sea ice	Thermodynamic only	Dynamic and thermodynamic	Dynamic and thermodynamic	Dynamic and thermodynamic	Dynamic and thermodynamic	Dynamic and thermodynamic	Dynamic and thermodynami
Treatment of atmosphere-ocean coupling	Flux-adjusted	Flux-adjusted	Flux-adjusted	Flux-adjusted	Not flux-adjusted	Not flux-adjusted	Not flux-adjusted
Treatment of multiple greenhouse gases	No,CO_2 used as surrogate	No,CO_2 used as surrogate	No,CO_2 used as surrogate	No,CO_2 used as surrogate	Yes	Yes	Yes
Treatment of sulfate chemistry	Albedo change only	Albedo change only	Albedo change only	Albedo change only	Yes,with reduced sulfur emissions	Sulfate loading specified from NCAR CSM	Yes
Equilibrium temperature response of system model to CO_2 doubling	3.5°C 6.3°F	2.6°C (4.1°C for AGCM with simple ocean) 4.7°F (7.4°F)	2.6°C 4.7°F	3.4°C 6.1°F	2.0°C 3.6°F	2.0°C 3.6°F	3.3°C 5.9°F
Year when results from 1900 to 2100 simulation were made available	1998	1998	1998 (but only through 2049)	1999	1999	1999	2000

[7] Note that although vegetation is an important feature of the land surface that can affect the climate,human-induced changes in future vegetation cover and changes in vegetation due to changes in climate are not yet being treated in these climate models.

- be models that are well-documented and whose groups are participating in the development of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in order to ensure comparability between the US efforts and those of the international community;
- provide a capability for interfacing their results with higher-resolution regional modeling studies (e.g.,mesoscale modeling studies using resolutions finer by a factor of 5 to 10);and
- allow for a comprehensive array of their results to be provided openly over the World Wide Web.

Including at least the 20th century in the simulation adds the value of comparisons between the model results and the historical record and can be used to help initialize the deep ocean to the correct values for the present-day period. Having results from models with specific features,such as simulation of the daily cycle of temperature,which is essential for use in cutting edge ecosystem models, was important for a number of applications that Assessment teams were planning. Despite uncertainties surrounding available emissions scenarios,using results with consistent assumptions about increases in greenhouse gases and sulfate aerosols helps to ensure that the assessment efforts of the various regional and sector teams can be combined into a consistent national synthesis and could then be interfaced with international assessments.

These restrictions led to a decision to consider mainly model simulations that used emissions scenarios that were close to the IPCC's "IS92a" scenario (see IPCC,1992) (see box,"What Does the IS92a Scenario Assume?") so that there could be ready comparison with international studies and analyses. As shown in Figure 6,the net radiative forcing for

What Does the "IS92a" Scenario Assume?

To prepare a projection of future changes in climate,a scenario of future concentrations of greenhouse gases must be developed. This is often done by starting with a scenario for changes in emissions of greenhouse gases. The future emissions scenario most used for analysis throughout the 1990s,including to drive model simulations of climate change,has been the IS92a scenario. This scenario is near the middle of the range of six peer-reviewed scenarios of possible alternative futures published by the IPCC in 1992 (IPCC,1992). Based on calculations done with models of greenhouse gas and aerosol concentrations,the IS92a scenario results in a climate forcing that is similar to that used in the two models chosen for primary use by the National Assessment. The recently published set of IPCC 2000 emissions scenarios finds that the net radiative forcing of this emissions scenario (i.e., greenhouse gas induced warming minus aerosol induced cooling influence) is still well within the range of what the IPCC has recently concluded are plausible scenarios for how energy technologies,energy use,economic development,and population growth of the 21st century may evolve (IPCC,2000).

The IS92a scenario makes a number of assumptions based on current and projected trends and expectations. Like each of the IPCC's 1992 scenarios,it assumes that the nations of the world will implement no major changes in their policies that would limit the growth of activities that are contributing to climate change. The scenario also assumes that global population will approximately double over the 21st century and that continued economic growth at rates typical of the recent past will raise total economic output by a factor of about 10; growth by this amount would mean that global average per capita economic activity would go up by a factor of 5. Because of increasing efficiencies and new technologies,the scenario assumes world energy growth will,however, only need to increase by about a factor of 4. To meet this increase in energy demand, energy derived from fossil fuels (coal,oil,and natural gas) is projected to more than double (increased use of coal,however, would increase CO_2 emissions by a factor of about 3). To provide the rest of the energy, the IS92a scenario assumes that energy derived from non-fossil fuel energy sources (e.g.,solar, wind,biomass, hydroelectric,and nuclear) will increase by a factor of about 15. The scenario assumes that this growth in non-fossil energy sources will occur without any implementation of climate-specific policies because the costs of these energy sources will decline relative to fossil fuels. If this scenario comes to pass,it would mean that the fraction of energy coming from non-fossil sources would rise from just over 10% of all energy now to over 40% by 2100. Scenarios forecasting less rapid availability of non-fossil technologies would lead to greater CO_2 emissions to meet the same growth in population and economic activity;scenarios leading to reduced CO_2 emissions would require some combination of more rapid increases in efficiency improvements, faster development of non-fossil technologies,a slower rate of economic development,and reduced population growth.

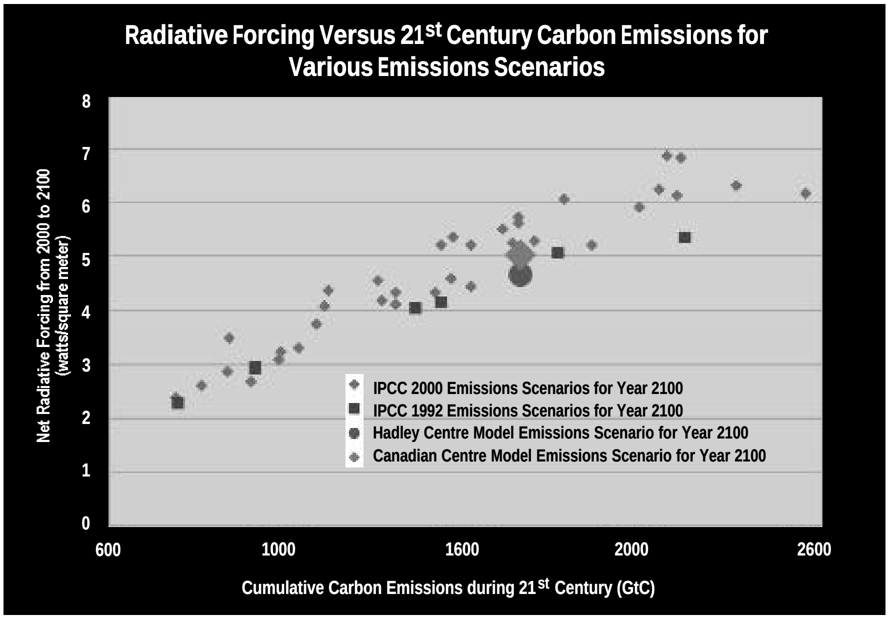


Figure 6: Comparison of the projections of total carbon emissions and overall human-induced radiative forcing for the six emissions scenarios prepared by the IPCC in 1992 (IS92 scenarios; IPCC, 1992) and the 35 emissions scenarios prepared by the IPCC in 2000 for which radiative forcing could be estimated (SRES scenarios; IPCC, 2000). These scenarios are based, although in different ways, on projected changes in emissions resulting from changes in population, economic development, energy use, efficiency of energy use, the mix of energy technologies, etc. The horizontal axis gives the total emissions of fossil fuel-derived carbon dioxide projected for the 21st century (in billions of tonnes of carbon, GtC). For reference, if the current level of global carbon emissions is maintained from 2000 to 2100, cumulative emissions over the 21st century would be roughly 650 GtC. Assuming no climate-related controls on emissions are introduced, this value is near the lowest value projected by any of the scenarios for the 21st century. The vertical axis gives the projected change in net radiative forcing at a pressure level approximating the tropopause (in watts per square meter) for all human-induced changes in greenhouse gases and aerosols (both direct and indirect contributions) over the 21st century using relationships employed in the IPCC Second Assessment Report (IPCC, 1996a; Smith et al., 2000), including the uptake of CO_2 by the oceans and land. Radiative forcing is important because it is the driving force for global warming; for reference, the projected change in radiative forcing up to the year 1992 is about 1.6 watts per square meter (IPCC, 1996a). The figure also shows the net radiative forcing and the approximate emissions of carbon used in the Hadley and Canadian scenarios. For these scenarios, which increase the equivalent CO_2 concentration by 1% per year, the carbon emissions are estimated by calculating the emissions needed to match the net radiative forcing after subtracting the radiative effects of other greenhouse gases and aerosols based on the average of IS92a and IS92f scenarios, and is an amount between the IS92a and IS92f scenarios. Based on these calculations, the Canadian and Hadley scenarios lie near the mid-range of the proposed scenarios in terms of both carbon emissions and net radiative forcing. See Color Plate Appendix.

the 21st century for the IS92a emissions scenario is near the mid-range of radiative forcing scenarios constructed based on the new set of emissions scenarios prepared by the IPCC (2000). The new scenarios suggest that the upper limit of possible increases in radiative forcing by 2100 is greater than for the IS92 emissions scenarios due to the recent recognition that significantly intensified use of fossil fuels could lead to substantial increases in emissions of methane,carbon monoxide,nitrogen oxides,and volatile organic compounds that would significantly increase the concentration of tropospheric ozone,a strong greenhouse gas. What is clear from this diagram,and is discussed more fully later in the text for the particular models used,is that the IS92a emissions scenario is a quite plausible choice for consideration if the results from only one emissions scenario are available. However, it must be emphasized that the climate model results that are available are simply one representation of what could happen,and are not predictions or forecasts of what might actually happen. This restriction could start to be relaxed in future assessments by considering results from a wider range of climate models and a wider range of emissions scenarios.

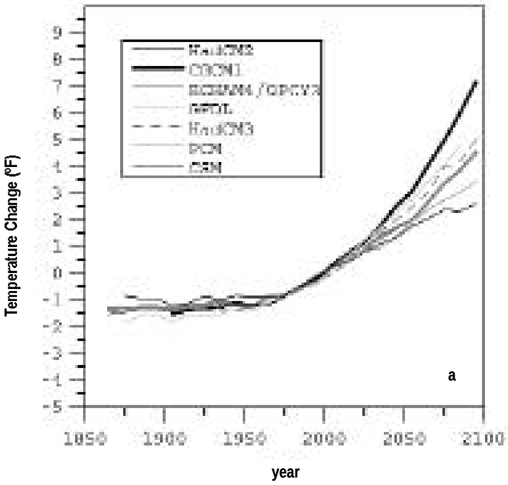
In the selection of the particular set of model results to be used for the Assessment,a number of additional constraints were also considered. For example, time and computer resource constraints generally prevented the completion of a new set of model simulations with these models specifically designed for this Assessment. Given the limited duration of the Assessment,and the desire to process the GCM results through the VEMAP processing package in order to better account for changes in mountainous regions,it was essential that scenarios be completed early in the assessment process (i.e.,mid to late 1998) in order to enable timely availability of processed model results. In addition,the limitations in capabilities and resources have meant that the set of cases and situations that all teams would be asked to use needed to be kept to a minimum. For these reasons,it was necessary to limit the selection to a minimum,but representative,set of model simulations.

Given these guidelines and considerations,the results from particular simulations of two models were selected to be the primary sources of simulation-based projections for this first National Assessment. The specific simulations selected were those runs that are closest to the IS92a emissions scenario from the GCMs developed by the Canadian Centre for Climate Modelling and Analysis (henceforth referred to as the “Canadian model scenario”) and the Hadley Centre for Climate Prediction and Research of the Meteorological Office of the United Kingdom ("Hadley model scenario," specifically the simulation using the HadCM2 GCM). Although careful consideration was given, the timing and types of simulations available from US modeling centers did not meet as many of the important criteria as the models selected (see NRC, 1998), although results from US modeling groups were able to be used by some regional teams and for some types of investigations.

Using the results from more than one major modeling center helps to capture a sense of the range of conditions that may be plausible in the future, even though the range of possible futures is likely to be broader due to the wide range of possible emissions scenarios as well as uncertainties arising from model limitations. Both of the models selected are coupled ocean-atmosphere models that are well documented and have been peer-reviewed by the scientific community (Boer et al., 1984, 2000b; Johns et al., 1997). Both models include the day-night cycle, which enables them to provide estimates of changes in minimum and maximum temperature. Both models reasonably represent the broad scale features of the global climate, including the major high and low pressure centers and the major precipitation belts that generate the weather. Even though each simulation can take several hundred hours on the fastest supercomputers that are available (Karl and Trenberth, 1999), both models have available ensembles of simulations (Mitchell et al., 1995; Mitchell and Johns, 1997; Boer et al., 2000a).

Although the fundamental physical principles driving these models are similar, there are differences in how, and even whether, the models incorporate some important processes. Therefore, there are some differences in the results of these models. One important factor in causing these differences is the uncertainty remaining in how best to represent such processes as changes in cloud cover in response to global climate change (e.g., see Mitchell et al., 1987). Because of such uncertainties, it is considered important to use models representing a range of possible values in impact studies. In addition, it needs to be noted that none of the model projections consider the potential influences of changes in natural forcings, even though it is likely that fluctuations will continue to occur as a result of variations in solar forcing and occasional volcanic eruptions (Hyde and Crowley, 2000).

Global Mean Temperature Anomalies (a)



U.S. Mean Temperature Anomalies (b)

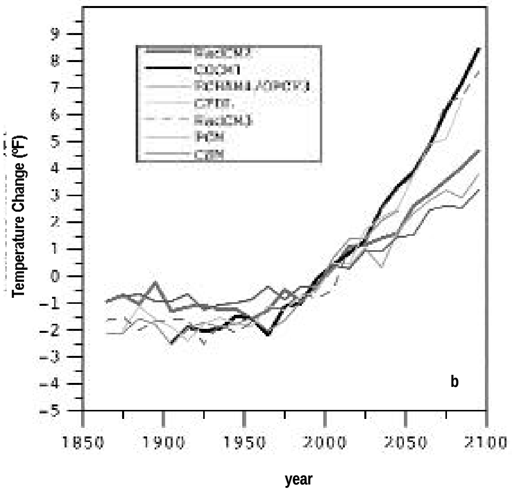


Figure 7: Comparison of the annual average changes in (a) global average surface air temperature (°F), and (b) US average surface air temperature (°F) from the Canadian model scenario and Hadley model scenario simulations used in the National Assessment and from the simulations of other modeling groups, including a very recent result from the Hadley Centre model version 3, Germany's Max Planck Institute/German Climate Computing Center (DKRZ), NOAA's Geophysical Fluid Dynamics Laboratory, and from the Parallel Climate and the Climate System models from the National Center for Atmospheric Research (which used a slightly lower greenhouse gas emission scenario and a significantly lower sulfate emissions scenario than the other models). Decadal means have been plotted to suppress the natural year-to-year variability. The baseline period is 1961-1990. The anomalies are with respect to the year 2000, calculating the values from a 2nd order polynomial fit over adjacent decades. See Color Plate Appendix.

Figure 7 and Table 2 provide a comparison of the projected changes in annual average surface temperature for the globe and for the US based on results from the Canadian and Hadley models. Results are

Table 2: Model-Simulated Changes in 20th and 21st Century Surface Temperatures for the US

Model simulated changes in annual-average surface temperature for the 20th and 21st centuries based on linear fits to the decadal average values derived from the model simulations with comparison to estimates of observed changes for the 20th century and the range of warming projected by the IPCC (1996a) for the various emission scenarios and climate model sensitivities.

Source of Estimate	Simulated Change in Global Average Surface Temperature		Simulated Change in Average Surface Temperature for Conterminous US	
	20th Century	21st Century	20th Century	21st Century
Hadley - Version 2	1.0˚F 0.55˚C	4.7˚C 2.6˚C	0.8˚F 0.4˚C	4.7˚F 2.6˚C
Canadian Centre	1.2˚F 0.7˚C	7.5˚F 4.2˚C	1.9˚F 1.05˚C	9.0˚F 5.0˚C
Max Planck Institute (MPI)	1.0˚F 0.55˚C	3.4˚F* 1.9˚C	1.6˚F 0.9˚C	4.1˚F* 2.3˚C
Geophysical Fluid Dynamics Laboratory (GFDL)	1.4˚F 0.8˚C	5.7˚F* 3.2˚C	1.65˚F 0.9˚C	7.8˚F* 4.3˚C
Hadley - Version 3	1.1˚F 0.6˚C	5.6˚F 3.1˚C	1.4˚F 0.8˚C	8.85˚F 4.9˚C
Parallel Climate Model	0.9˚F 0.5˚C	3.7˚F 2.0˚C	0.7˚F 0.4˚C	4.1˚F 2.3˚C
Climate System Model	0.9˚F 0.5˚C	2.8˚F 1.5˚C	0.7˚F 0.4˚C	3.3˚F 1.8˚C
Observed (Quayle,1999 and Karl et al.,1995b)	0.7-1.4˚F 0.4-0.8˚C		0.5-1.4˚F 0.3-0.8˚C	
IPCC (1996a) for 1990 to 2100 (uncontrolled sulfur emissions)		1.6-6.3˚F^ 0.9-3.5˚C^		
IPCC (1996a) for 1990-2100 (level sulfur emissions)		1.4-8.1˚F^ 0.8-4.5˚C^		

*Estimates for less than the full 21st century have been linearly extrapolated to develop an estimate for change over the full century (MPI from 2049 to 2100;GFDL from 2090 to 2100).

^For estimates for just the 21st century, about 0.2-0.3˚F (0.1-0.2˚C) must be subtracted,depending on scenario considered.

also provided for a set of simulations done with other models,some of which became available after processing of results for use in impacts studies had been completed. The Canadian and Hadley simulations each use an emissions scenario for changes in greenhouse gas and aerosol concentrations over the 21st century that is designed to represent the IS92a (or no policy intervention) case of the IPCC (1992). New simulations are being carried out by the world's modeling groups for the new range of climate scenarios developed by the IPCC (2000). As an example of the results of this type of simulation, the figure also includes the newer simulations with the NCAR CSM and PCM models that use a lower emissions scenario than IS92a for greenhouse gases and aerosols (ACACIA-BAU, see Dai et al.,2001) and that are carried out with a model with a climate sensitivity in the lower part of the range of 2.7 to 8.1˚F (1.5 to 4.5˚C). It is important to note that these model results also indicate that substantial warming occurs even assuming that emissions are reduced significantly below the IS92a scenario.

Although the emissions scenarios are the same for the Canadian and Hadley simulations,the Canadian model scenario projects that the world will warm more rapidly than does the Hadley model scenario. This greater warming in the Canadian model scenario occurs in part because the Hadley model scenario projects a wetter climate at both the national and global scales,and in part because the Canadian model scenario projects a more rapid melting of Arctic sea ice than the Hadley model scenario. Results from other models,with the exception of the latest results from the National Center for Atmospheric Research (Dai et al.,2001),are generally within or slightly below the lower bound of this range. The larger reduction in the NCAR model results from the slower rise in greenhouse gas concentrations that is assumed and due to a projected increase of low cloud cover that is not evident in simulations by other models,although these effects are somewhat offset by reduced loadings of sulfate aerosols. Compared to the range suggested for the year 2100 in the IPCC results (IPCC,1996a),the Hadley model scenario projects warming for the 21st century that is slightly above the central IPCC estimate of about 4˚F (2.4˚C) after adjusting for the change in baseline years. The Canadian model scenario projects global average warming that is slightly above the high-end of the IPCC suggested range if sulfur emissions are not controlled,but within the range if they are assumed to be controlled. The greater warming for the Canadian model (Hengeveld,2000),as for the Hadley-3 model,is likely a result of their higher climate sensitivity. While neither the Hadley nor Canadian model scenarios projects a rate of warming coincident with the low end of the IPCC range,this lower bound is also generally not consistent with estimates of climate sensitivity derived from comparison of model simulations with the paleoclimatic record or with the extent of warming that has occurred over the last two hundred years.

All of the models,with the exception of the Hadley version 2 GCM (HadCM2),project greater warming over the US than for the globe as a whole. The variation of results among model results is also greater for the US than for the globe. It is especially interesting that the projected warming due to these changes in greenhouse gas concentrations is very rapid after the mid-1970s,when much of the recent warming began. As an indication of how the sequential improvement of models by the various groups may change the results,it is instructive to compare the results from the HadCM2 that were used in this Assessment,with the results from the Hadley version 3 GCM (HadCM3) that were not available in time for full use in this Assessment. The more recent Hadley model results suggest significantly more warming over the US than the Hadley model selected for this Assessment. Recognizing that all model results are plausible projections rather than specific quantitative predictions,the primary models used for this Assessment project that the average warming over the US will be in the range of about 5 to 9˚F (about 2.8 to 5˚C). However, given the wide range of possible emissions scenarios and uncertainties in model simulations,it is possible that the actual increase in US temperatures could be higher or lower than indicated by this range. Such a warming is approximately equivalent to the annual average temperature difference between the northern and the central tier of states,or the central and the southern tier of states.

Figure 8 provides similar information for projected changes in precipitation. For the globe,the two primary Assessment models represent a range of plausible conditions that are typical of results from other climate models that have used the same emissions scenario,although the simulation of NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) does suggest an even greater increase in global precipitation than either of these primary models. Over the US,the spread among model results is greater than over the globe due to the patchier nature of precipitation and changes in precipitation. The Hadley model scenario projects a very large increase in precipitation (which is one reason its temperature increase is lower than for other models) whereas the Canadian model scenario results show an increase mainly in the second half of the 21st century. The greater variability of the precipitation results,compared to the temperature results, reflects the larger natural variability of precipitation. By using the selected results from the Canadian and Hadley models, we are not only capturing results for differing model sensitivities,but also,to a large extent, for much of the wet/dry and hot/warm range of future climate conditions generated by the wider set of climate models. As such,these cases seem quite representative of the types of conditions that could occur.

While the available information provides quite plausible estimates for the future,there are important limitations that need to be recognized:

- Each model simulation provides a snapshot of the temporal and spatial variations of the climate as the global climate is evolving through time in response to changes in greenhouse gases and aerosols. Because of inherent variability in the model that results from small differences in the initial model conditions,only by employing an ensemble of simulations would we be able to assess the statistical significance of the model results for any decade over this interval. When an ensemble of simulations is analyzed, the long-term trends in variables have been found to be generally consistent across multiple simulations, but quite variable for particular years, decades, and locations.

- The particular simulations we have selected reflect only one particular emissions scenario rather than a range of emission scenarios (the emissions scenario being used for the model runs we are using is described in a subsequent section). For the future, the actual emissions of greenhouse gases and aerosols are likely to be different than the baseline used. For example, it is quite possible that emissions of both greenhouse gases and aerosols may be lower (as a result of societal development, control measures, etc.) or higher if oil shale and coal become the fuels of choice throughout the world. Changing the emissions scenario would give different results, although the rate of climate change over the next few decades is not likely to differ significantly from the model results because of the momentum created by climate and global energy systems.
- Use of only two model simulations provides a limited opportunity to investigate the consequences of climate variability and change. To help overcome this limitation, regions and sectors have been asked, as explained earlier, to look both at the historical record and to consider cases that reflect educated guesses based on the nature and importance of specific regional and sector sensitivities. One tool developed for use in the sensitivity analyses is the "Probabilities of Temperature Extremes" CD-ROM that has been developed by NCDC. Other approaches focus on drawing information from the regional paleoclimatic record.

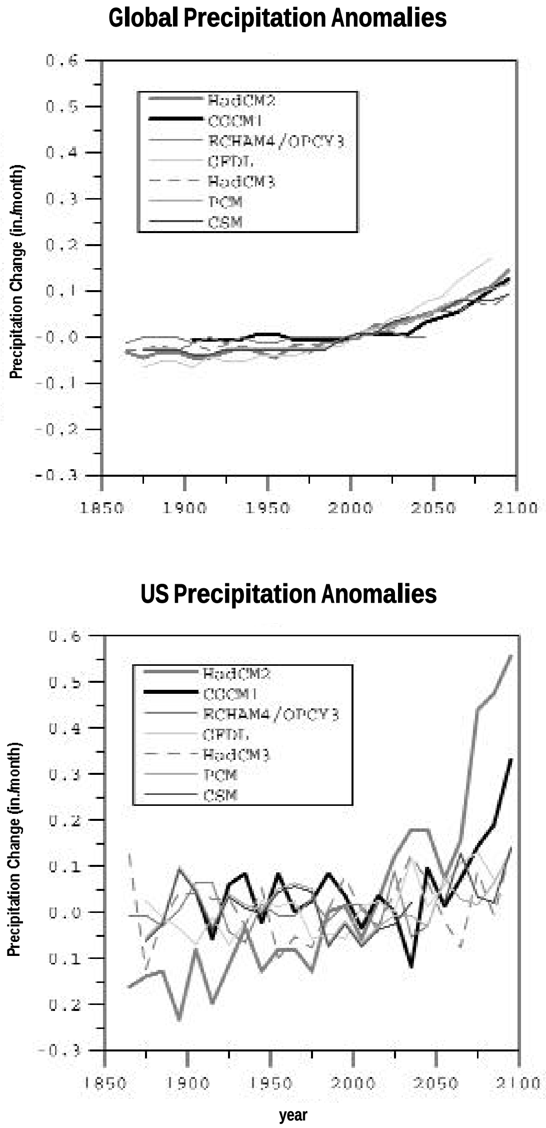


Figure 8: Comparison of the annual average changes in (a) global average precipitation (inches per month), and (b) average precipitation over the US from the Canadian model scenario and Hadley model scenario simulations used in the National Assessment and from the simulations of other groups (same as for Figure 7). The baseline period is assumed to be 1961-1990. Although decadal means have been applied to suppress year-to-year fluctuations, the greater variability of precipitation than temperature still reveals significant variations due to natural factors; the magnitude, although not the timing, of the remaining fluctuations may be considered plausible. The anomalies are with respect to the year 2000, calculating the values from a 2nd order polynomial fit. See Color Plate Appendix.

Recognizing the limitations in the minimum strategy approach that could be proposed for the entire set of Assessment teams, some groups have had the resources available to carry through additional impact studies using results from the models developed at the National Center for Atmospheric Research (NCAR), NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), NASA's Goddard Institute for Space Studies (GISS), and the Max Planck Institüt/Deutsches Klimarechencentrum (MPI/DKRZ, referred to simply as MPI) in Germany. To support this extended effort, access to the wider set of climate information is provided through the National Assessment web site.

While GCMs have shown significant improvement over recent decades, and the models used in the Assessment are considered among the world's best, there are a number of shortcomings that arise in applying the models to study potential regional-scale consequences of climate change. For this Assessment, several types of effort have been used to start to address these problems. Of most importance for the analyses done as part of the National Assessment, the results of the GCMs have been passed through the VEMAP processing algorithms so that information could be provided at a scale that

Normalization of Results from Climate Models

While the Canadian and Hadley models both provide reasonable simulations of the large-scale features of the 20th century climate over the US,there are differences in the absolute values of temperature and precipitation that could affect many types of impact studies if adjustments were not made. For the 20th century, this process is accomplished by simply driving the impact models with the observed climatic conditions rather than the model-generated conditions. For studying the 21st century, this procedure is not possible as observations of the future are not available. Instead,the assumption is made that the differences between models and observations for the 20th century are systematic – that is,that the differences between models and observations are a result of limitations in the model formulation and will be present in simulations for both the 20th and 21st centuries. If this assumption is valid,then the changes in climate due to human activities can be determined by taking the difference between a model simulation with increasing concentrations of greenhouse gases and one simulation without such changes and adding the difference to the observations for the 20th century to yield plausible estimates for the changing climatic conditions of the 21st century. Although this assumption is certainly not completely valid,it is likely to be sufficiently valid that the uncertainties introduced in making this assumption will, for many types of situations,be of less importance than uncertainties resulting from other factors (e.g.,the differences between models,uncertainties in climate sensitivity to changes in greenhouse gases,uncertainties in impact models,etc.).

To carry out this normalization of the model results using the differencing approach,and to provide improved spatial resolution of key climate variables,the VEMAP methodology applied initially to the observed station data was used to process the Canadian and Hadley model scenarios of climatic changes during the 21st century. This procedure was done by interpolating the monthly average changes calculated by the models to the VEMAP grid and then basing the scenario for the 21st century on the model calculated increment to the 20th century climate baseline. In the case of temperature,the adjustment was carried out by adding the model estimate for the monthly average change in temperature from the model's 1961-90 baseline to the local value of the observed monthly baseline temperature for the same period. For precipitation,the adjustment was made based on the multiplying by the ratio (percentage) change calculated by the model. In this way, projections for the 21st century were made for changes in mean maximum surface air temperature,mean minimum surface air temperature,and total precipitation on a monthly basis. A weather generator was used to derive daily values for these variables,and incoming solar radiation and humidity were then derived from these variables. These data sets are available at http://www.nacc.usgcrp.gov/scenarios and values for particular regions or time periods can be extracted by going to http://eos-webster.sr.unh.edu.

While this application of the VEMAP technique of using the changes calculated by the models to simulate the changes to the historical record provides a practical way of accounting for the systematic offsets between modeled and locally observed conditions,this technique is not without its limitations. For example,care must still be taken when analyzing the effects of special situations where thresholds effects might occur (e.g.,the presence or absence of snow cover in mountainous regions) resulting in projected changes that may be too strong or too weak. Also,assuming that the temperature changes will be the same in valleys and on mountaintops fails to deal with the effects of inversions and the special weather conditions of mountain regions. Using the ratioing approach to estimate precipitation change also assumes,at least to some extent,that weather systems will be of the same type,being different only in overall intensity or number, while not recognizing that changes in storm direction into mountainous regions could have a large effect. Darwin (1997) argues that at least some of these limitations can be reduced,especially in desert regions, by using absolute amounts of precipitation to make the adjustment;however, in mountainous regions,this approach seems to fail to deal with the strong gradients in precipitation with altitude. Alcamo et al.(1998) have compared the risk for worldwide natural vegetation using the two approaches,and find a lower risk using the ratioing approach that is used in the Assessment than the difference-adjustment technique,suggesting that the conclusions drawn in this Assessment may be somewhat conservative,although this uncertainty is likely less than the uncertainty resulting from the differences in the model projections.

What is most clear is that, for future assessments,meso-scale models need to be used to more rigorously and accurately simulate regional patterns of changes in precipitation (and such efforts are already underway in a couple of the regions).

was comparable to the information in the data sets for the historical period and in a way that accounted for at least some of the shortcomings and biases in the models. In particular, the model scenario results used in the impact assessments were adjusted to remove the systematic differences with observations that are present in the GCM calculations in particular regions due to mountainous terrain and other problems. The VEMAP normalization process is described in the box "Normalization of Results from Climate Models."

In addition,some regional teams have applied other types of "down-scaling"techniques to the GCM results in order to derive estimates of changes occurring at a finer spatial resolution. One such technique has been to use the GCM results as boundary conditions for mesoscale models that cover some particular region (e.g.,the West Coast with its Sierra Nevada and Cascade Mountains). These models are able to represent important processes and mountain ranges on finer scales than do GCMs. However, these simulations are very computer intensive and it has not yet been possible to apply the techniques nationally or for the entire 21st century. With the rapid advances in computing power expected in the future,this approach should become more feasible for future assessments. To overcome the computational limitations of mesoscale models,other participants in the Assessment have developed and tested empirically based statistical techniques to estimate changes at finer scales than do the GCMs,and these efforts are discussed in the various regional assessment reports. These techniques have the important advantage of being based on observed weather and climate relationships,but have the shortcoming of assuming that the relationships prevailing today will not change in the future.

CLIMATE MODEL SIMULATIONS OF THE 20th CENTURY FOR THE US

An important measure of the adequacy of the applicability of these models for simulation of future climatic conditions is to compare their results for simulation of the climate of the 20th century over the US with observations[8]. In conducting these simulations,the models are driven by observations and, particularly for aerosols, reconstructions of the changing composition of the atmosphere. While one might want the simulations to match observations very accurately, several complications must be accounted for in making the comparisons. First,the model simulations have not been designed to,and cannot be designed to, exactly reproduce the climate of the 20th century. One reason that reproduction of the 20th century climate is not possible is that observations are poor or entirely lacking of changes in some of the factors that could lead to part of the naturally induced fluctuations in the climate. These factors include changes in solar radiation,[9] injection of volcanic aerosols into the stratosphere,and the state of the global ocean and ice sheets at the start of the century. Over the long term,omitting such natural forcing factors should tend to average out to a near zero net effect on global average temperatures. For this reason,the effect of these omissions is often assumed to be small over periods of many decades compared to the steady and long-term growth of the greenhouse effect. Second,because of the chaotic nature of the climate, we cannot expect to match the year-by-year or decade-by-decade fluctuations in temperature that have been observed during the 20th century. Third,these particular model simulations do not yet include consideration of all of the effects of human-induced changes that are likely to have influenced the climate,including changes in stratospheric and tropospheric ozone and changes in land cover (and associated changes relating to biomass burning, dust generation,etc.). Finally, while it is desirable for model simulations not to have significant biases in representing the present climate,having a model that more accurately reproduces the present climate does not necessarily mean that projections of changes in climate developed using such a model would provide more accurate projections of climate change than models that do not give as accurate simulations.This can be the case for at least two reasons. First,what matters most for simulation of changes in future climate is proper treatment of the feedbacks that contribute to amplifying or limiting the changes,and accurate representation of the 20th century does not guarantee this will be the case. Second,because projected changes are calculated by taking differences between perturbed and unperturbed cases,the effects of at least some of the systematic biases present in a model simulation of the

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[8] It should be noted that while we are interested in changes over the US,these changes are in many cases determined by how well the model represents changes in the global scale features of the climate that in turn then affect what is happening over the US and in particular regions. Although the models selected do include flux adjustments to reduce drift in global average temperatures,these flux adjustments have only a limited influence on determining the patterns of continental-scale climate simulated by these models. It should also be noted that models not including flux adjustments give a generally similar pattern and range of model projected changes in climate.

[9] The newest GCM simulations are beginning to investigate the effects of past variations in solar radiation on climate, even though reconstructions of past levels of solar output are uncertain.

present climate can be eliminated. While potential nonlinearities and thresholds make it unlikely that all biases can be removed in this manner, it is also possible that the projected changes calculated by such a model could turn out to be more accurate than simulations with a model that provided a better match to the 20th century climate.

Recognizing these many limitations, evaluation of the simulations of the Canadian and Hadley models are presented here to give an indication of the general adequacy of the models for use in these studies. Analyses at the global scale by the two modeling groups indicate that there is general agreement with the observed long-term trend in temperature over the 20th century, although there is significant variation over decadal time scales (e.g., Johns et al.,1997; McFarlane et al.,1992;Flato et al.,2000). As shown by Stott et al.(2000),simulations with the Hadley model also show that, by accounting for changes in greenhouse gas concentrations,sulfate aerosols,and solar forcing,there is a close similarity between the observed and the modeled climates,with both model simulations warming about 1˚F during the 20th century and showing a roughly similar temporal pattern even though not all influences were considered.

Few of these comparisons have focused on the character of the simulations at the continental and national scale that are of interest in this Assessment, and so this section presents a selection of these model results. At these scales,so many types of comparisons can be made,and there are so many ways to display and interpret the results,that the set of comparisons included here is augmented by additional comparisons available on the Web site[10] to provide the interested reader the opportunity to gain a more complete perspective. The set of figures here have been chosen to illustrate that results from these models,while not predictions,are plausible and suitable for use in investigating the potential consequences of climate variability and change for the US.

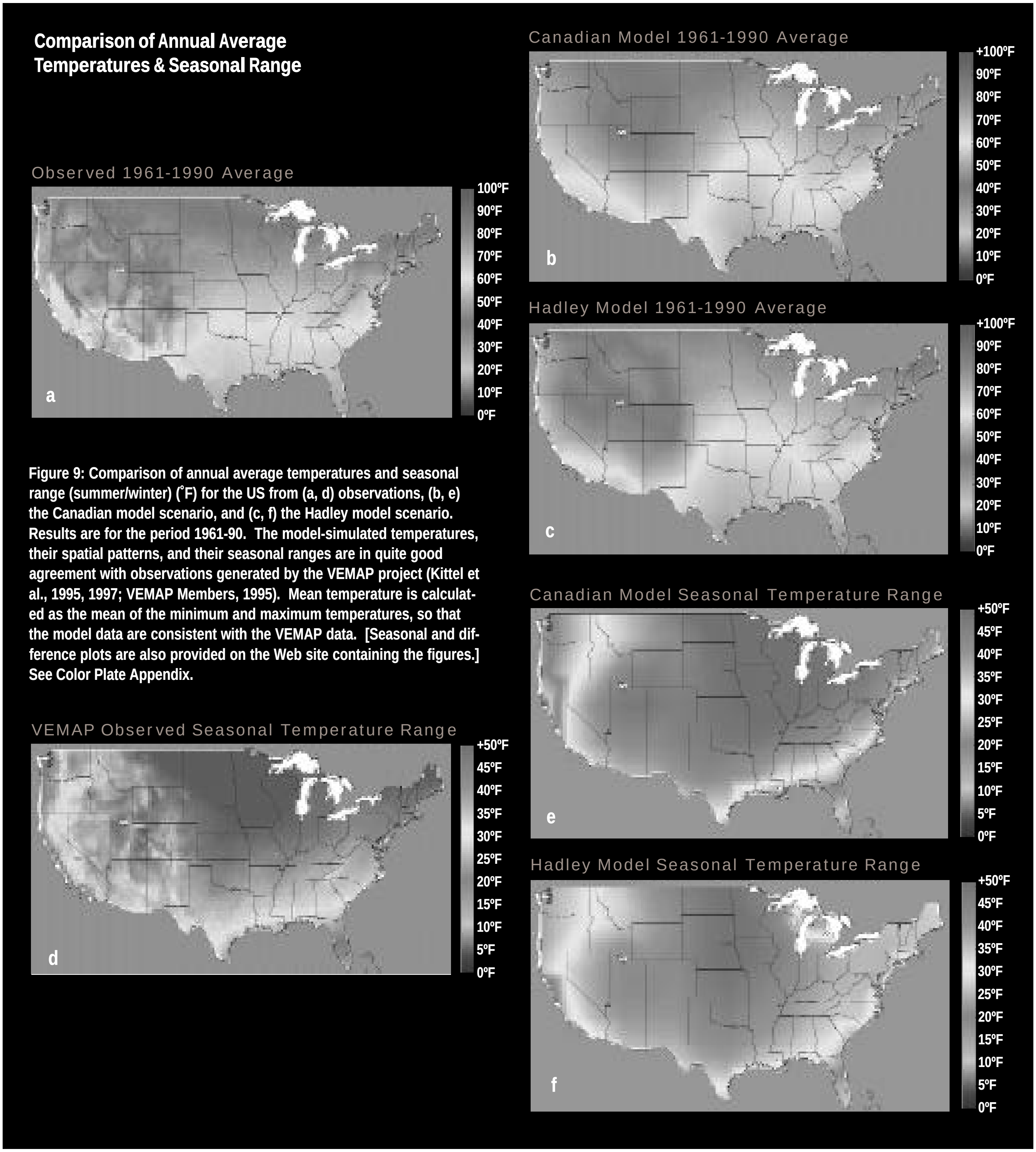
Figure 9 compares the Canadian and Hadley model scenarios to observations,presenting results for annual average temperature and for seasonal temperature range[11] (summer average temperature minus winter average temperature) for the period 1961-1990;this period, by common convention,is considered the baseline climate period. For annual average temperature,the model results and observations have quite similar values and distributions across the US,with average temperatures exceeding 80˚F (about 28˚C) along the southeastern edges of the US and near 40˚F (about 5˚C) across the north-central US. The maps of the seasonal range in temperature across the US (summer minus winter) show that the seasonal ranges of temperature for the models extend from about 5˚F (about 3˚C) near southern and southwestern coastal regions to over 50˚F (about 28˚C) in the northern Great Plains,in reasonable concurrence with observations.

The comparisons also show that the models are a bit warmer than observations along mountain ridges (e.g.,the Sierra Nevada and Cascade Mountains) and a bit colder than observed over mountain basins. Doherty and Mearns (1999) report that both models exhibit large year-round cold biases over mountainous regions of the West when compared to the Legates and Wilmott (1990a) climatology. However, that climatology likely has a warm bias (making the models look cold) because most observing stations are located in valleys in mountainous regions. The VEMAP surface climatology used in the National Assessment comparisons improved on the Legates and Wilmott climatologies by adding in information from a large number of high altitude stations and otherwise accounting for the effects of mountains. Compared to this presumably more accurate representation of the observed conditions,the model differences with observations are smaller, but not eliminated.

Differences with observations remain particularly large over the southern Rocky Mountains and Great Basin (see Web site for a map of actual differences). These differences are most likely due to the effects of smoothing the mountain ridges and uplifting the mountain valleys to match the relatively coarse resolution available in current climate models (figures of the differences in topographic height of models and observations are also shown on the Web site). Both primary models also exhibit a warm bias over Hudson Bay during winter that extends southward into the northern US. This bias may be partly due to insufficient observational measurements over Hudson Bay itself, so that the observed surface temperature is likely more representative of cold land areas than of water bodies covered by sea ice (Doherty and Mearns,1999). Other biases may well reflect the limited spatial resolution and representation of climatic processes in the models. For example,both models also have a warm bias during summer in the central Great Plains and Midwest that probably reflects inadequate treatment of summer convection and soil moisture processes. This bias

[10] See additional figures at www.cgd.ucar.edu/naco/found/figs.html.

[11] Figures showing the model projections of temperature for the summer and winter seasons and for differences between simulations and observations are available on the Web site.



Comparison of Annual Average Temperatures & Seasonal Range

Observed 1961-1990 Average

Canadian Model 1961-1990 Average

Hadley Model 1961-1990 Average

VEMAP Observed Seasonal Temperature Range

Canadian Model Seasonal Temperature Range

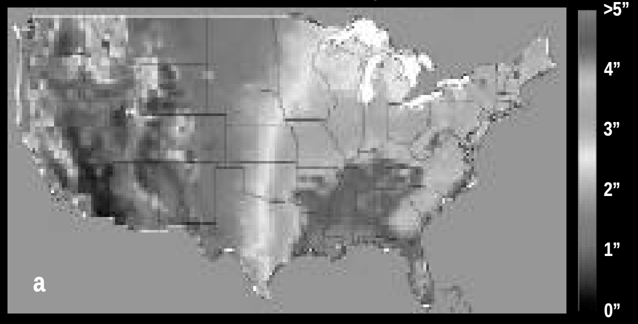
Hadley Model Seasonal Temperature Range

Figure 9: Comparison of annual average temperatures and seasonal range (summer/winter) (˚F) for the US from (a, d) observations, (b, e) the Canadian model scenario, and (c, f) the Hadley model scenario. Results are for the period 1961-90. The model-simulated temperatures, their spatial patterns, and their seasonal ranges are in quite good agreement with observations generated by the VEMAP project (Kittel et al., 1995, 1997; VEMAP Members, 1995). Mean temperature is calculated as the mean of the minimum and maximum temperatures, so that the model data are consistent with the VEMAP data. [Seasonal and difference plots are also provided on the Web site containing the figures.] See Color Plate Appendix.

extends further into the eastern US in the Canadian model scenario than in the Hadley model scenario. Over adjacent ocean areas,the Canadian model also indicates temperatures slightly above observations whereas the Hadley model indicates temperatures are slightly below observations,likely reflecting remaining problems with representation of coastal ocean areas (Doherty and Mearns,1999). These differences of several degrees can create problems in the direct application of model results,but the agreement of the overall patterns and seasonal ranges provides considerable confidence that the projected changes in temperature due to human influences are plausible for use in impacts studies.

Comparison of Annual Total Precipitation & Seasonal Range

VEMAP Observed Annual Precipitation



Canadian Model Annual Precipitation

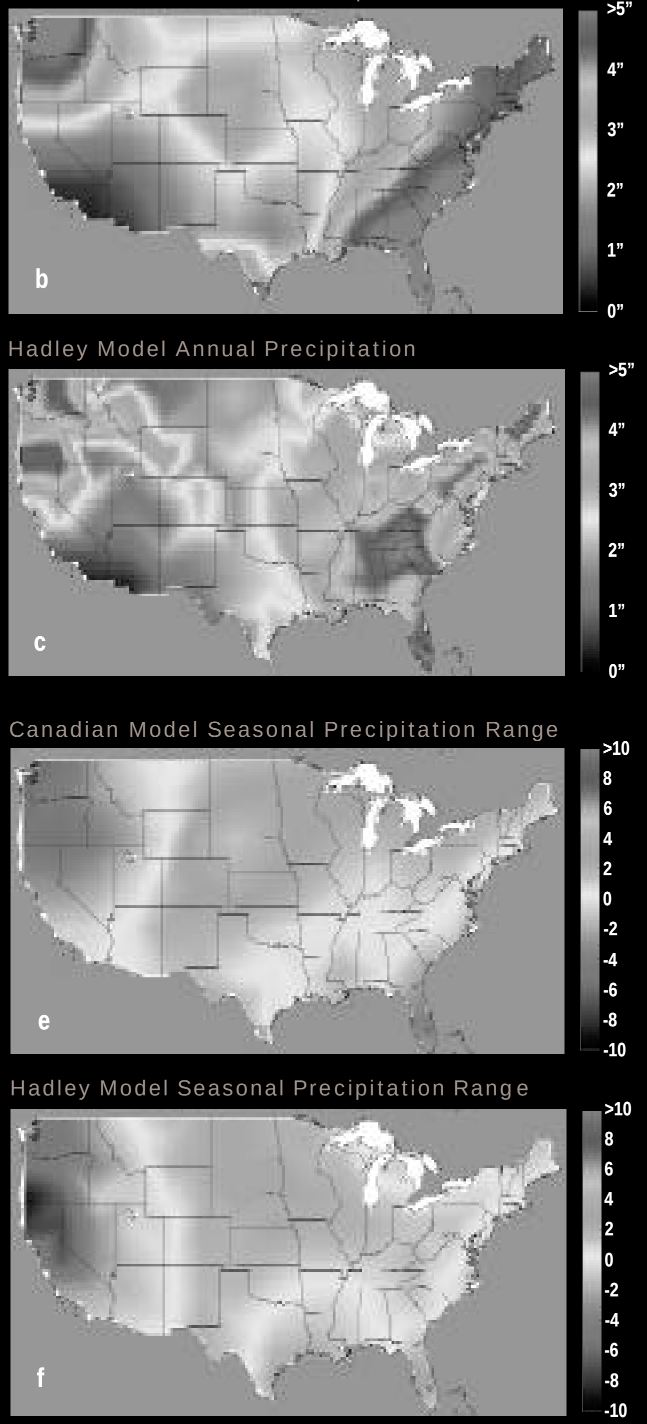


Figure 10: Comparison of annual total precipitation and seasonal range (summer minus winter) in inches per month for the US from (a,d) observations, (b,e) the Canadian model scenario, and (c,f) the Hadley model scenario. Results are average inches/month for the period 1961-90. The model-simulated precipitation totals, their spatial patterns, and their seasonal ranges are in reasonable agreement with observations generated by the VEMAP project (Kittel et al., 1995, 1997; VEMAP Members, 1995). [Difference plots are also provided on the Web site containing the figures.] See Color Plate Appendix.

VEMAP Observed Seasonal Precipitation Range

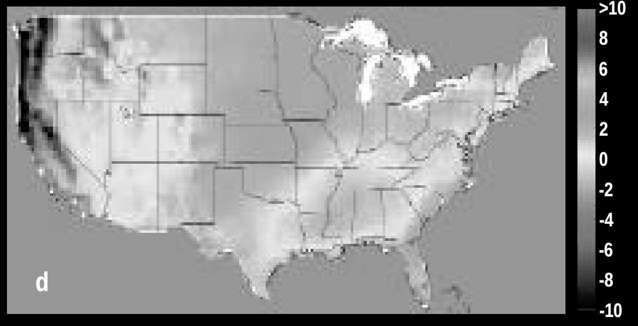


Figure 10 presents similar results for annual total precipitation and seasonal range (summer minus winter, in inches/month). Precipitation amounts in complex terrain are highly variable as a result of the local interaction of storms with mountains and local variations in the surface warming that drives convective rain systems (Legates and DeLiberty, 1993; Legates 1997). The relative coarseness of the model resolution means,therefore,that agreement is not likely to be as good,especially over the western US. Both models and observations (from VEMAP and Legates and Wilmott,1990b) show a similar range from a minimum in the dry areas of the Southwest to much larger amounts over other parts of the

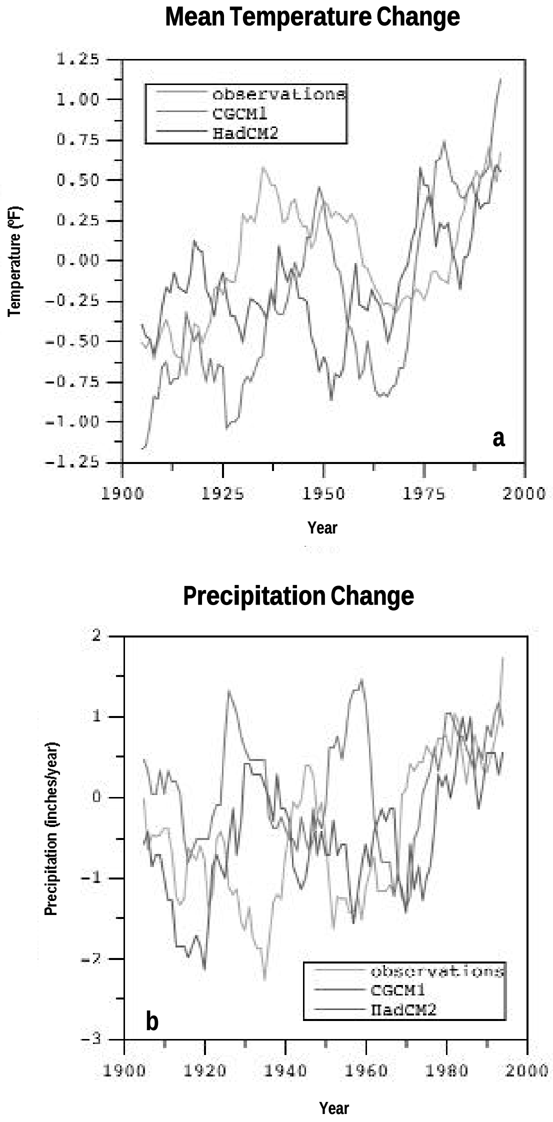


Figure 11: Time histories of the changes in (a) annual average temperature (°F), and (b) annual total precipitation (inches per year) for the 20th century based on observations and on simulations from the Canadian and Hadley models, calculated as 10-year running means from 1900 to 2000. Mean temperature is the actual mean temperature from the models, rather than the mean of the minimum and maximum temperatures. Anomalies are shown with respect to 1961-1990. In these simulations, unlike in intercomparisons of the atmospheric models as in the AMIP project (Gates et al., 1999), the ocean temperatures are freely calculated and the concentrations of greenhouse gases and aerosols are imposed; natural forcings, such as changes in solar radiation and volcanic eruptions that are likely affecting the observed climate are not, however, being treated in the models because observations of their precise radiative influences are not available. See Color Plate Appendix.

country. Although the very broad-scale patterns are similar, the role of mountain chains in concentrating precipitation into particular locations is much more evident in the observations than in the models with their very smoothed representation of mountain ranges. The pattern of the seasonal range is also plausibly represented,with the indication that precipitation in the West occurs much more in winter than summer whereas over the rest of the country there tends to be a modestly larger amount in summer. Overall,the model results show broad agreement with observations, except in the Canadian model over Florida. Similarities,however, are evident in the simulation of high amounts of precipitation in the West in winter and low amounts in summer giving a negative seasonal range,and a smoother seasonal cycle in the eastern US. However, there are important differences,especially in the regions of mountainous terrain where observations of precipitation are also problematic due to the great spatial variability.

As for the temperature differences,differences with observations arise because the models do not fully represent the high reach of mountain ridgelines. Because of this discrepancy, the models do not create as much precipitation along the Pacific coast ridgelines as is observed,allowing more precipitation further inland. For the rest of the country, comparisons by Doherty and Mearns (1999) indicate that the models have a wet bias over northeastern North America in spring and summer, and a dry bias in southern North America in both summer and winter. In our comparisons,the Canadian model (but not the Hadley) shows a wet bias in the northeastern US,but a dry bias when integrated over the whole country. The biases in coastal regions may result from the relatively coarse resolution of the models,which does not allow adequate representation of the relatively small-scale spatial patterns of the sea breeze and other coastal meteorology. Also, the tropical rainbelt created by the Intertropical Convergence Zone (ITCZ) does not extend far enough northward in either model,creating dry biases in some of the equatorial regions of the Northern Hemisphere. That there are differences that must be accounted for in the analyses becomes especially clear when focusing on very particular regions (e.g.,Florida),and the Web site provides difference maps for simulations of the total and seasonal precipitation.

Because some impact studies require scenarios of changes in day-to-day variability in the weather, comparison should also be made over this time scale, considering, for example,the adequacy of model simulations of the frequency, intensity, and amounts of precipitation. Unfortunately, such detailed comparisons are only beginning to be carried out and so caution must be exercised in interpretations than depend on these results. Nonetheless,as for temperature,if account is taken of systematic differences, the model results would seem to give a plausible set of baseline conditions to use in estimating changes to temperature and precipitation that could occur as the climate changes.

In evaluating model performance,it is also important to look at how well the models simulate the temporal variations of climatic conditions in the immediate past. Figure 11 shows a comparison over the US of the observed and modeled time histories of changes in annual average temperature and annual total precipitation during the 20th century. Remembering that complete agreement of each climate fluctuation should not be expected due to the natural variability of the climate,these plots indicate that the models generally have the right magnitude and duration of natural climate anomalies and that, with the exception of the start of rapid warming late in the century in the Canadian model scenario, the trends are plausibly similar. The Web site provides diagrams that go beyond these comparisons to provide estimates of the actual values of temperature and precipitation,thereby illustrating the systematic differences that are present between the models and observations. These differences arise both because of limitations in the models (e.g.,inadequate resolution,inadequate representation of various processes,etc.) and shortcomings in the monitoring network (e.g., few stations at high latitudes, etc.). To the extent that these differences are systematic,the model projections of changes can be used if care is taken in working near thresholds such as the freeze line. To the extent that the differences are inherent in the treatment of climate processes and how they might respond with a different climate,uncertainties are introduced into the climate scenarios, again emphasizing that these result must be viewed as scenarios rather than predictions.

While these analyses indicate that the model results are generally similar to observations,it is clear that systematic errors are present,especially in mountainous areas. To account for these differences,historical analyses have generally been based on compilations of observational data,such as the USHCN or VEMAP data sets, rather than numerical model results,and appropriate adjustments need to be made when applying model results for the future (as explained in the box on page 28 on Normalization of Results).

SCENARIOS FOR CHANGES IN ATMOSPHERIC COMPOSITION AND RADIATIVE FORCING FOR THE 21st CENTURY

Projecting changes in climate for the 21st century requires not only a tested climate model,but also a scenario for the development and evolution of the human activities that are expected to affect the climate. In particular, projections of climate change require a projection of how atmospheric composition will be changing in the 21st century as a result of the ongoing use of fossil fuels and the release of other greenhouse gases[12]. To provide the basis for such estimates,scenarios of societal and technological evolution during the 21st century must be developed;these in turn can be used to develop emissions scenarios. The accuracy of these scenarios is necessarily limited by uncertainties in insights and assumptions about what will happen many decades into the future. Because of the resulting uncertainties,the concentration scenarios that are used,like the climate scenarios,cannot be viewed as predictions of the future. Instead,they must be treated as plausible estimates of future conditions that are appropriate for use in exploring vulnerabilities through analysis and assessment.

A range of scenarios has been developed by a number of groups to describe how atmospheric concentrations of CO_2, other GHGs,and aerosols may change in the future. These scenarios are generally based on projections of future changes in population,energy technology, economic development, environmental controls,and other factors. The 1992 scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC,1992) have become widely used because of the international effort that went into their consideration[13]. The set of 1992 IPCC greenhouse-gas emission scenarios was based upon six plausible demographic and socioeconomic scenarios that spanned a wide range of possibilities for population growth,types of energy use,and rates of economic growth. The range of projected emissions for the 21st century is quite broad (see IPCC,1992 and Figure 6).

The central baseline (sometimes called “business-as-usual”) estimate from the set of IPCC 1992 scenarios is closely comparable to the radiative forcing scenario represented by a 1% per year compounded

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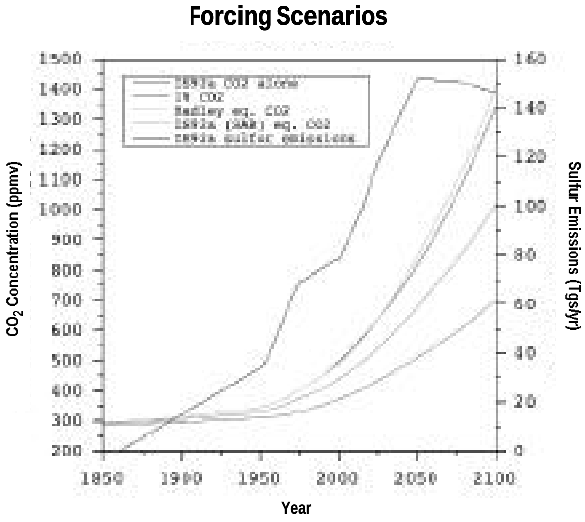
[12] Note that for the purposes of these studies,the level of solar insolation and the occurrence of volcanic eruptions are assumed to remain as they were for the 20th century. Even though changes are likely (e.g., see Hyde and Crowley, 2000),the net effect of these changes are likely to be small in comparison to the human-induced influences on radiative forcing.

[13] These scenarios are presently being updated as part of the effort leading up to the IPCC's Third Assessment Report (IPCC,2000). The newer scenarios tend to span a similar range to the 1992 scenarios.

increase in the equivalent CO_2 concentration that has been used by most climate modeling groups to generate their central estimates of potential climate change for the 21st century. This scenario has been taken as the baseline scenario for this study because of its wide use,because it represents neither maximum nor minimum emissions projections (see Figure 6),and because this Assessment did not have the resources to either construct better alternative scenarios or ensure that such scenarios would be used by the climate modeling groups for calculations that would be available in time for impact evaluation as part of this Assessment. Although the IS92a emissions scenario tended to overestimate greenhouse gas emissions during the 1990s (Hansen et al.,1998),it is not clear that the recent tendency toward lower emissions compared to IS92a will persist as the global economy recovers from its recent recession. In particular, the new IPCC (2000) scenarios suggest a wide range of possible future emissions scenarios,some higher and some lower than the IS92a scenario (see Figure 6). To the extent that actual greenhouse gas emissions might be greater or less than this central scenario over the long term, the climatic changes at a given time would be greater or less. Alternatively, the climatic changes that are projected with this scenario would be projected to occur either earlier or further in the future,although the difference would likely be less than one or two decades. Although the potential consequences of a somewhat faster or slower rise in greenhouse gas emissions has not yet been evaluated,it seems likely that such changes in emissions scenarios would have a relatively small influence over the climate changes projected for the first half of the 21st century.

Figure 12 shows the projected changes in CO_2 and equivalent CO_2 concentration for the IS92a scenario (projected changes in the concentrations of other greenhouse gases are described in IPCC,1992) and the 1% per year change in equivalent CO_2 concen-


Forcing Scenarios

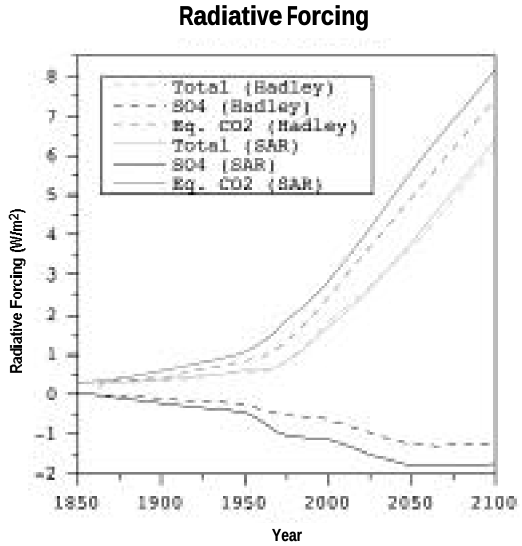

Radiative Forcing

Figure 12: Comparison of different projections for aerosol effects and for (a) the CO_2 and equivalent CO_2 concentrations, and (b) the associated radiative forcings for the period 1850-2100. In the top figure, the lavender line shows the IPCC's IS92a scenario estimate of the CO_2 concentration; values prior to 1990 are based on observations. Based on this projection, the CO_2 concentration would rise to about 705 ppmv in 2100 from a level of about 353 ppmv in 1990. Because many of the climate models treat the effects of the set of human-affected greenhouse gases by use of an equivalent CO_2 concentration, the green line shows the scenario for the equivalent CO_2 concentration, which rises to about 1022 ppmv in 2100 from a value of about 410 ppmv in 1990. For this curve, the equivalent CO_2 concentration is calculated so as to incorporate the radiative effects of changes in the concentrations of all greenhouse gases using the IPCC radiative forcing equivalents (the conversion factor is 6.3 based on Appendix 2 in IPCC, 1997). The light blue line shows the equivalent CO_2 concentration that results from using the Hadley radiative forcing equivalents to approximate the IS92a scenario; the conversion factor used is 5.05 (John Mitchell, personal communication). Using the Hadley conversion factor, the equivalent CO_2 concentration for the IS92a scenario would rise to about 1409 ppmv in 2100. The red line shows that the Hadley IS92a equivalent CO_2 scenario is quite well fitted by use of a 1% per year compounded increase in the Hadley equivalent CO_2 concentration. In this case, the CO_2 equivalent concentration in 2100 reaches about 1346 ppmv. The deep blue line shows the IPCC IS92a scenario for sulfur emissions, which shows a rise until about 2050, when emissions roughly level off. While there are some differences in the projected concentrations of equivalent CO_2 between the IPCC (1996a) and the Hadley model scenario, the bottom figure shows that these differences are mostly overcome when comparing the radiative forcings that are projected by the IPCC and are actually used in the Hadley model scenario. The red and blue lines, respectively show the radiative forcings as projected by the IPCC (solid lines) and as included in the Hadley model (dotted lines). For both forcings, the Hadley model projects slightly less influence than the projections using the IPCC conversion factors. When these forcings are combined, as shown by the green lines, the net radiative forcings projected by the IPCC and used in the Hadley model 1% per year scenario are very close. See Color Plate Appendix.

tration. For the National Assessment, the IS92a time history of the CO_2 concentration (which rises to about 708 ppmv by 2100) has been used in the studies of the consequences of a rising CO_2 concentration for plants, coral, etc. However, because concentrations of CH_4, N_2O, and CFCs are also changing, the model simulations need to be forced by the net radiative effect of these greenhouse gas changes. This consideration is implemented in the Hadley and Canadian models by increasing the equivalent CO_2 concentration by 1% per year (compounded) starting in 1990 to account for the combined radiative effects of all the greenhouse gases (Boer et al., 2000a). Thus, while the 1990 concentration of CO_2 is about 354 ppmv, the model uses an equivalent CO_2 concentration of about 420 ppmv to account for the effects of the other greenhouse gases. For the year 2100, rather than reaching a CO_2 concentration of about 708 ppmv, an equivalent CO_2 concentration of about 1055 ppmv is reached (note that the 1% per year case is slightly higher than this concentration, actually being closer to case IS92f). In terms of radiative forcing, the 1% simplification overestimates the net forcing in 2100 of all greenhouse gases by about 10% compared with IS92a (of course, there are other scenarios that have higher forcing than IS92a). As shown in Figure 12, the IS92a scenario used by the models also significantly increases sulfate emissions (and therefore sulfate aerosol loadings) until about 2050, after which levels are projected to remain roughly constant. The net changes in forcing for both the Hadley and Canadian model scenarios are, as indicated in Figure 6, near the middle of the range for all emissions scenarios.

In that sulfate aerosols contribute significantly to air pollution and acid rain, the newer scenarios in IPCC (2000) suggest that sulfate aerosol levels (and so their cooling influence) will be lower than in IS92a, thereby raising the overall warming influence. In addition, the new scenarios suggest that significant increases in the use of fossil fuels will lead to increased emissions of methane, carbon monoxide, nitrogen oxides, and volatile organic compounds, which will lead to significant increases in both regional and hemispheric levels of tropospheric ozone, a strong greenhouse gas.

What is quite clear from Figure 6 is that the radiative forcing could be either higher or lower than the case that has been the most frequent reference case for the modeling groups and is being used in this Assessment. The normal way to treat such a range of possible futures would be to treat a range of possible future conditions rather than rely on only one case. In this first National Assessment, constraints on time and resources, however, have forced a limitation to considering the consequences of only one concentration scenario. While this approach is a limitation that should be relaxed in future assessment efforts, the constraints of this limitation are reduced by the recognition that much of the climate change over the next few decades will be due to already recorded changes in atmospheric composition. In addition, with the momentum created by the world's present use of fossil fuel energy, deviations in the concentration scenario for the various GHGs are likely to have only a limited influence on the climate over the next few decades. To explore this issue further, a later section of this chapter does summarize the climatic consequences of using a scenario that moves toward stabilization of the atmospheric CO_2 concentration at double its preindustrial value. However, even if such a stringent emissions limitation were imposed now, the effect on CO_2 concentrations and climate would be relatively modest during the early 21st century before increasing and becoming quite significant during the 22nd century.

CLIMATE MODEL SCENARIOS FOR CHANGES IN TEMPERATURE, PRECIPITATION, SOIL MOISTURE, AND SEA LEVEL OVER THE US FOR THE 21st CENTURY

Temperature and Heat Index

All climate models project significant warming for the 21st century. Results shown in Figure 7 clearly indicate that the global warming projected for the 21st century will be significantly greater than during the 20th century. This increase in the rate of warming is due to both the continuing rise in the CO_2 concentration projected for the 21st century and the continuing response of the climate system to the increasing rate of rise in the CO_2 concentration in the second half of the 20th century. Figure 7 also demonstrates that the projections for warming over the US are very likely to be greater than for the global average, both because warming is greater over land areas than over ocean areas and because the US is located in mid-latitudes. This figure also shows that, although the rate of warming is not like-

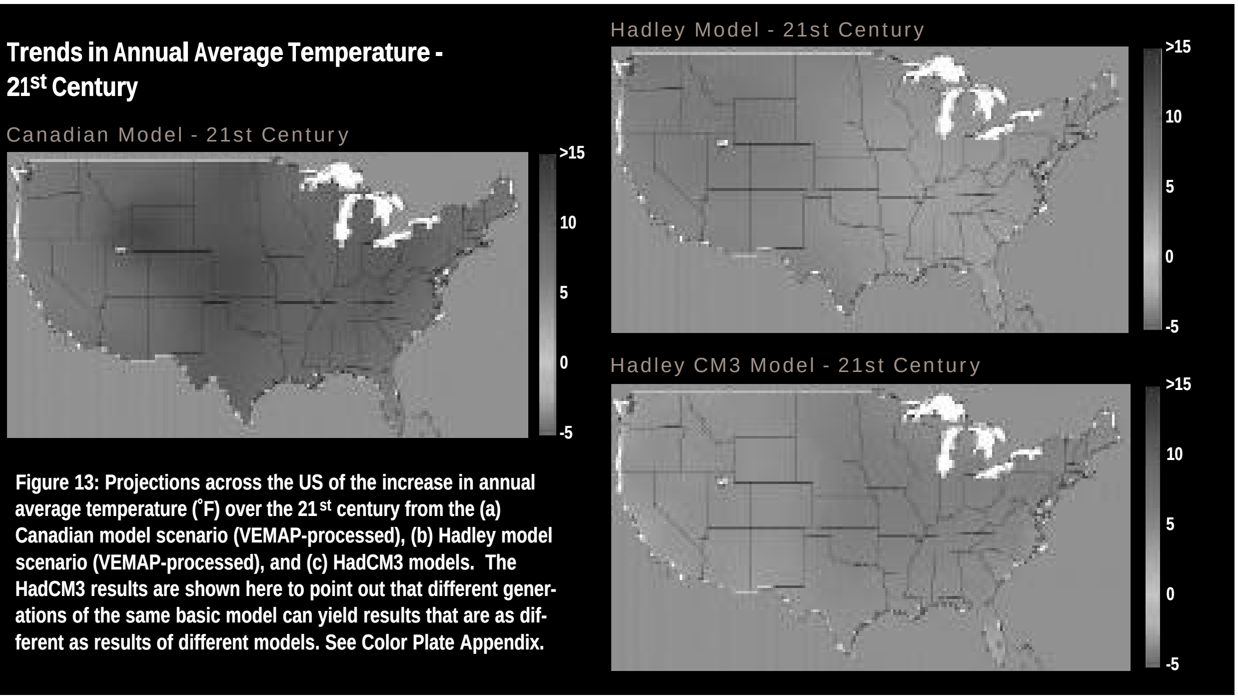
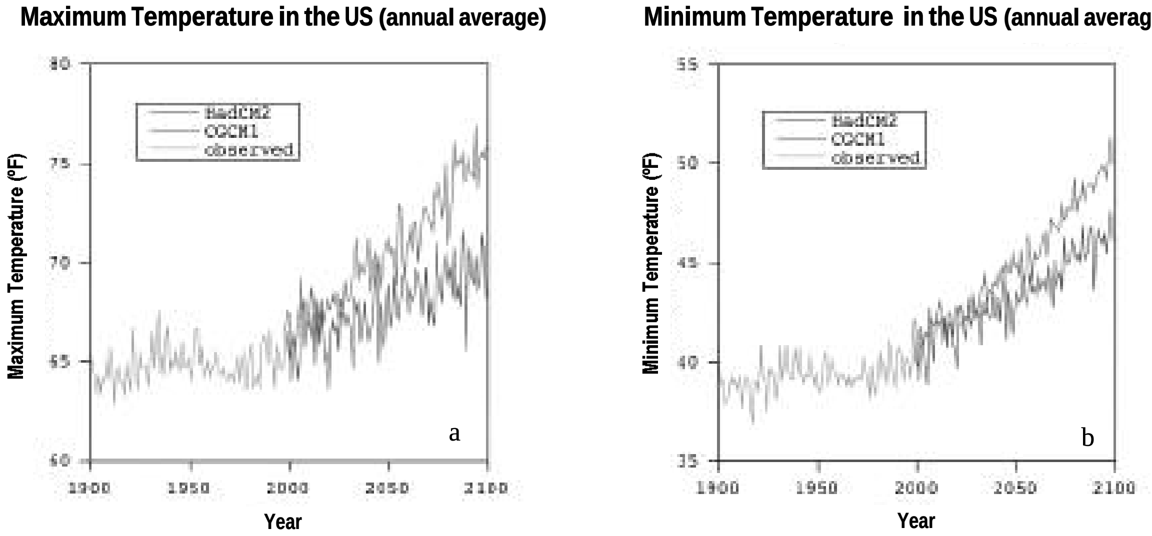


Figure 13: Projections across the US of the increase in annual average temperature (˚F) over the 21st century from the (a) Canadian model scenario (VEMAP-processed), (b) Hadley model scenario (VEMAP-processed), and (c) HadCM3 models. The HadCM3 results are shown here to point out that different generations of the same basic model can yield results that are as different as results of different models. See Color Plate Appendix.

ly to be uniform over this period,the average rate warming rate is very likely to increase during the 21st century. This change in rate may occur in an uneven way, with some very warm years,and then some not-so-warm or even cooler years. Although we do not yet have the ability to forecast these short-term fluctuations precisely, the model scenarios clearly show that the long-term rate of warming is very likely to increase substantially over coming decades.

Figure 13 shows the annual average geographic patterns of the projected warming across the US as calculated by the Canadian and Hadley models[14]. The trends are in degrees (˚F) of warming per century and represent the expected warming for the several decades around 2100[15]. In the Canadian model scenario for the next 100 years,increases in annual average temperature of 10˚F (5.6˚C) are projected across the central US,with changes about half this large projected along the East and West Coasts. The projections indicate that the changes will be particu-

Figure 14: Time histories of (a) maximum and (b) minimum temperature over the US (˚F). The values prior to the present are based on observations from 1900-1998 (the HCN data set) and values for the future are based on the VEMAP version of the Canadian and Hadley model scenarios (i.e., in the VEMAP data sets, model projections of climate change are added to the observed 1961-90 baseline climate). See Color Plate Appendix.



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[14] Maps of projected changes for the winter and summer seasons are available on the Web site.

larly large in winter, with minimum temperatures rising more than maximum temperatures. Large increases in temperature are also projected over much of the South in summer. In the Hadley model scenario, temperatures in the eastern US are projected to increase by 3 to 5˚F (2-3˚C) by 2100. Regions across the rest of the nation are projected to warm by up to about 7˚F (4˚C). Such changes would be equivalent to shifting the climate of the southern US to the central US and the climate of the central US to the northern US.

Model results from the HadCM3 model are also shown in Figure 13. This model is a more recent version of the Hadley Centre model than was available at the start of this Assessment. This model shows greater warming in the eastern half of the US. This reinforces the point that although all the models agree that there will be a strong warming trend, projections of the spatial and temporal pattern of the warming differ among the models.

While the maps included in this chapter provide results for the conterminous 48 states, model results are also available for Alaska and for the Pacific and Caribbean Islands on the Web site. Both models project that Alaska will experience even more intense warming than the conterminous US[16]. In contrast, Hawaii and the Caribbean islands are likely to experience somewhat less warming than the continental US, because they are at lower latitudes and are surrounded by ocean, which warms more slowly than land. These results are shown in maps appearing in the respective chapters of this report. Although the details of the projected climate fluctuations over time are less reliable than the projections of the overall trends, it is useful to examine the projected time histories of the changes. Figure 14 shows the time histories for the projected changes over the US in the annual averages of minimum and maximum temperature for the two models. As is suggested by the maps, the time series show that the warming is projected to be greater in the Canadian model scenario than in the Hadley model scenario. The larger increase in minimum than maximum temperature indicates that nighttime temperatures are projected to increase more than daytime temperatures. Factors causing this difference could include the increase in downward infrared radiation, the increase in the dew point temperature, changes in cloud cover, changes in soil moisture, and changes in snow and ice cover, each of which would act to raise nighttime temperatures more than daytime temperatures. In addition, an increase in sulfate concentrations or increases in cloud cover might act to limit daytime warming by reflecting more solar radiation back to space. That both models suggest that minimum temperatures will rise more rapidly than maximum temperature is consistent with what has been observed over the past century (Easterling et al., 1997).

Although the two primary models used here project that the temperature increase will be greater in the western than in the eastern US, the intensification of the hydrologic cycle caused by the warming will also cause an increase in the amount of moisture in the air. This increase is particularly important for the southeastern and eastern US, where humidity is relatively high and upward trends in temperature are quite large (Karl and Knight, 1997). Figure 15 shows the projected increases in the heat index

July Heat Index Change - 21st Century

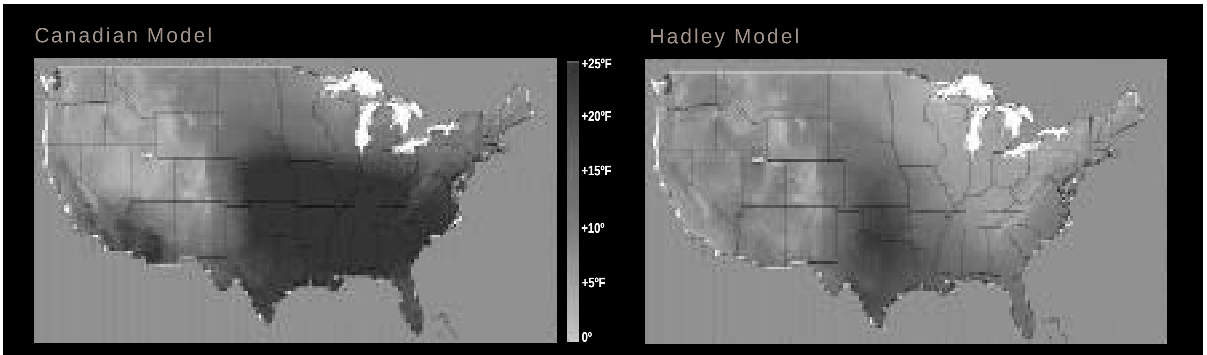

Figure 15: Projections across the US of the increase in the July heat index (˚F) over the 21st century (˚F per century) from VEMAP versions of the (a) Canadian model scenario and (b) Hadley model scenario. See Color Plate Appendix.

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[15] Because the model simulations are most valid over long-periods of time, these results are based on a linear fit to the model projected changes for the 21st century rather than being based on the differences between particular years or decades at the beginning and end of the century. This choice is intended to make clear that it is the overall century-long rate of change that is the result in which we can have the most confidence. Because of the long-term warming, great care should be taken in comparing this projected rate of change to observed changes over shorter periods because it is widely recognized that there will be considerable natural variability through the century as a result of the effects of natural influences such as solar variations, volcanic eruptions, and the ocean-atmosphere interactions that create such fluctuations as ENSO events.

[16] For results for Alaska, see http://www.cgd.ucar.edu/naco/alaska/tx.html.

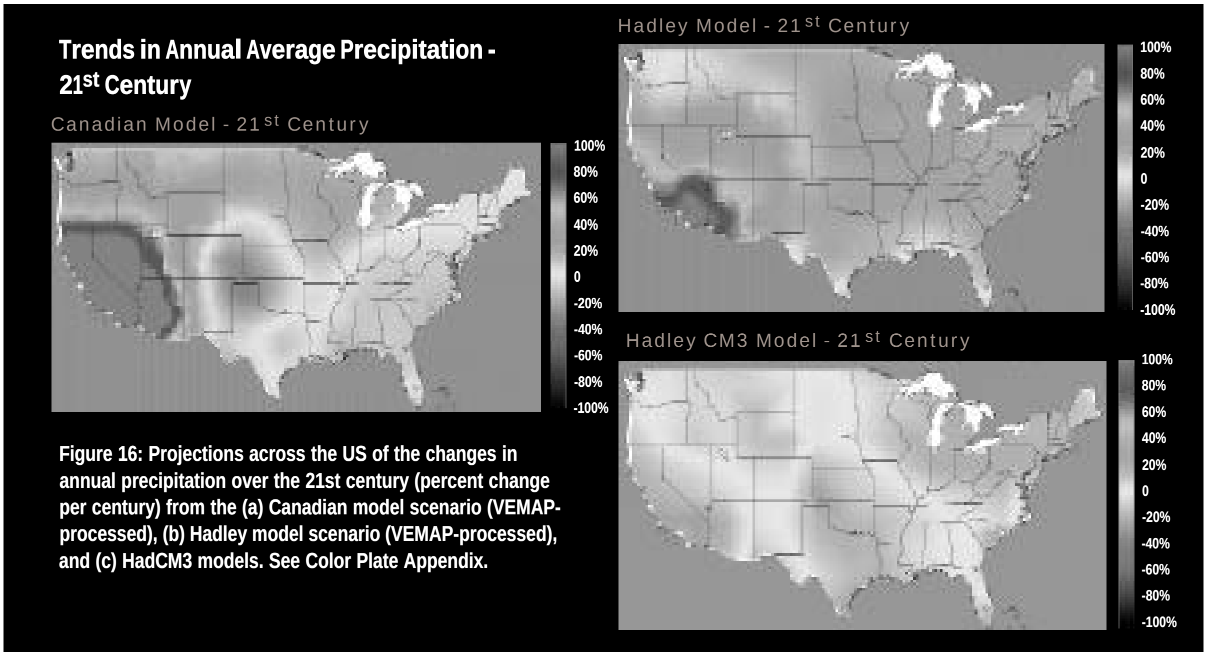

Figure 16: Projections across the US of the changes in annual precipitation over the 21st century (percent change per century) from the (a) Canadian model scenario (VEMAP-processed), (b) Hadley model scenario (VEMAP-processed), and (c) HadCM3 models. See Color Plate Appendix.

across the US based on the model projections for the changes in maximum temperature;similar results have been reported from the GFDL model (Delworth et al.,1999). The heat index is a measure of the rise of apparent temperature and is a good measure of discomfort because it combines both heat and humidity effects (Steadman,1979). These results indicate that, even though the relative humidity may drop slightly (not shown),the rise in the heat index will be more than double the actual rise in temperature across much of the South and East, making the projected warming in these parts of the country feel particularly significant. By the end of the 21st century, the heat index of the Northeast is likely to feel more like that of the Southeast today; the Southeast is likely to feel more like today’s south Texas coast;and the south Texas coast is likely to feel more like the hottest parts of Central America today.

Precipitation

Figure 16 shows the projected pattern of changes in precipitation across the contiguous US, expressed as a percentage change from the present amount[17]. The most noticeable feature in both models is a projected increase in precipitation in California and the southwestern US. The projected increase is larger in the Canadian than in the Hadley model scenario. This feature is a result of a warmer Pacific Ocean causing an increase mainly in wintertime precipitation. Although the projected changes over the Pacific Ocean are not well-established,particularly with regard to how El Niño conditions may change, both primary models project Pacific Ocean warming and a southward movement of the storm-generating Aleutian Low which would together lead to increased precipitation along the West Coast. For these conditions,a greater fraction of the increased wintertime precipitation would be expected to fall as rain rather than snow, causing,on average, a reduction in mountain snow pack. These changes are likely to increase wintertime and decrease summertime river flows in the West. Even with an accurate projection of Pacific Ocean changes,the regional pattern of this precipitation increase could only be roughly estimated due to the limited representation of the region’s mountains (e.g.,see Mearns et al.,1999). As global scale models improve, mesoscale models will be able to be used to explore this issue further.

Across the Northwest and over the central and eastern parts of the US,the precipitation projections from the models are in less agreement. The differences between model projections are likely a result of a number of factors. For example,the two models show different positions and intensities of the storm tracks in the Southeast during winter in their simulations of recent decades. The Canadian model scenario projects that there will be a decrease in annual precipitation across the southern half of the nation east of the Rocky Mountains. Decreases are projected to be particularly large in eastern Colorado and western Nebraska in the west central Plains,and in the southern states in an arc from Louisiana to Virginia. These projected decreases in precipitation are largest in the Great Plains during

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[17] Changes in the absolute amount of precipitation are shown in figures available on the web site.

summer and in the East during both winter and summer. In the Hadley model scenario,virtually the entire US is projected to experience increases in precipitation,with the exception of small areas along the Gulf Coast and in the Pacific Northwest. Precipitation is projected to increase in the eastern half of the nation and in southern California and parts of Nevada and Arizona in summer, and in every region except for the Gulf States and northern Washington and Idaho during the winter. However, while the Hadley (HadCM2) scenario used in this Assessment suggests greater precipitation in the Southwest,the more recent HadCM3 model suggests that there will be less rainfall in the Southwest;the projected pattern of change is similar to the Canadian model scenario in parts of the Southeast. Because of the differences among these results,the projected direction of the trend for changes in precipitation in any given region needs to be viewed as uncertain,although continuation of the increasing precipitation trend for the US as a whole seems plausible. Resolving these differences in precipitation projections will occur only by increasing resolution and implementing other improvements in the climate models.

Figure 17 provides the time histories of the projected changes in precipitation for the US. Both models project a long-term increase in total annual precipitation across the US. However, the time histories clearly indicate that the very large variability that currently exists is likely to continue,with the possibility of periods of both increased and even reduced precipitation within the overall upward trend.

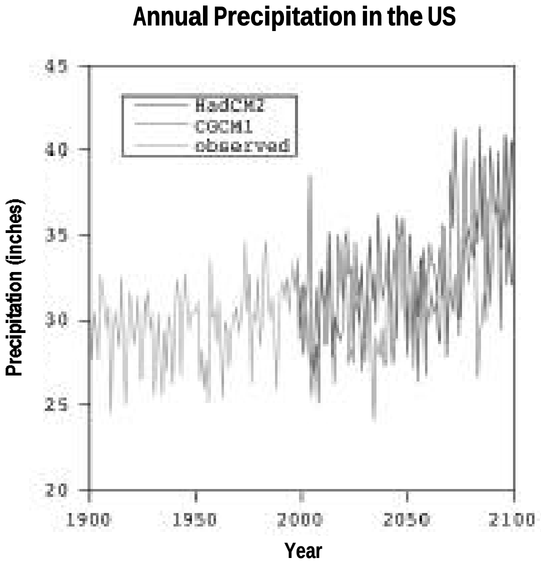

Figure 17: Time history of model projected changes in precipitation over the US (inches per year). The values prior to the present are based on observations from 1900-1998 (the HCN data set) and values for the future are based on the VEMAP version of the Canadian and Hadley model scenarios. See Color Plate Appendix.

Soil Moisture

Projections of changes in soil moisture depend on the balance between precipitation, evaporation, runoff, and soil drainage. By itself, an increase in precipitation would tend to increase soil moisture. However, higher air temperatures increase the rate of evaporation and may remove moisture from the soil faster than it can be supplied by precipitation. Under these conditions,some regions are likely to become drier even though rainfall increases. In fact, soil moisture has already decreased in portions of the Great Plains and Eastern Seaboard,including in some locations where precipitation has increased but air temperature has risen. Figure 18 shows the projected changes in the summer soil moisture across the US. In the Canadian model scenario,the Southeast and the region extending through the

Summer Soil Moisture - 21st Century

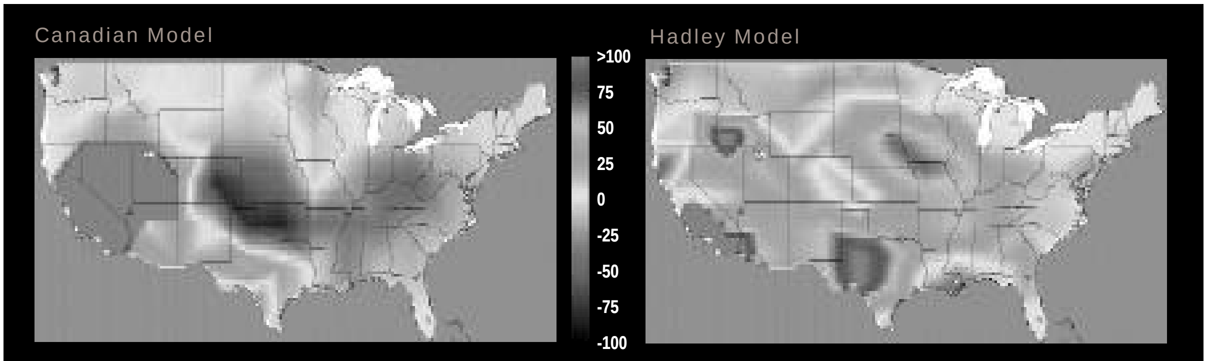

Figure 18: Projections across the US of changes in summertime soil moisture over the 21st century (percent change per century) from the (a) Canadian model scenario, and (b) Hadley model scenario. Figure prepared by the National Climatic Data Center. See Color Plate Appendix.

central US to just east of the Rocky Mountains are projected to experience the largest decreases in soil moisture. Increases in soil moisture are projected for the areas surrounding Iowa and from Utah to California. In the Hadley model scenario,summer soil moisture is projected to increase in the eastern half of the US and is generally unchanged or slightly decreased from the Rocky Mountains westward, except for Southern California.

Increased drought becomes a national problem in the Canadian model scenario and is also found in the GFDL model (Wetherald and Manabe,1999). Intense drought tendencies occur in the region east of the Rocky Mountains and throughout the Mid-Atlantic-Southeastern states corridor. Increased tendencies toward drought are also projected in the Hadley model scenario for the regions immediately east of the Rocky Mountains. California and Arizona, as well as the region from eastern Nebraska to the Virginia coastal plain are projected to have reduced drought tendency. The differences in soil moisture and drought tendencies are likely to be the most critical for agriculture, forests, water supply, and lake levels.

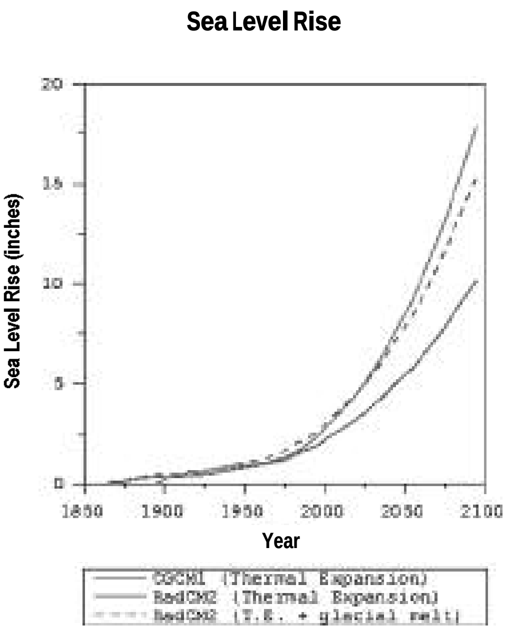

Figure 19: Historic and projected changes in sea level (inches above baseline) based on the Canadian and Hadley model scenarios. The Canadian model projection includes only the effects of thermal expansion of warming ocean waters (F. Zwiers, personal communication). The Hadley model simulation adds on the sea level increment of melting of mountain glaciers (Gregory and Oerlemans, 1998). Neither model includes consideration of possible changes of sea level (upward or downward) due to melting or accumulation of snow on Greenland and Antarctica. See Color Plate Appendix.

Sea Ice and Sea Level

The two primary model scenarios include projections of a decline in sea ice cover and a rise in sea level,both of which are of particular importance for assessing the potential consequences of climate change along coastlines. The Canadian model scenario projects that sea ice in the Arctic Ocean is very likely to melt completely each summer and be significantly reduced in winter thickness and extent by the end of the 21st century, whereas the Hadley model scenario envisions a slower process of melting. Observations indicate that the average depth of sea ice in the Arctic has dropped by 40%,from about 10 feet (3.1 meters) to about 6 feet (1.8 meters) over the past three decades (Rothrock et al.,1999);this suggests that the model projections of melting of sea ice in the future are likely to be quite plausible. Sea ice is particularly important for coastal regions because its presence suppresses waves from wintertime storms that erode coastlines. In addition,some marine species depend on the protection or convenience of sea ice to feed and reproduce,making the meltbacks ecologically important.

Because sea ice floats,its melting does not affect sea level. However, the melting of glaciers on land and the warming of ocean waters do cause sea level to rise. Over the 20th century, observations indicate that sea level has risen about 4 to 8 inches (10-20 cm). In estimating the potential rise in sea level during the 21st century, the Canadian model scenario includes consideration of only the sea-level rise caused by the warming of ocean waters (the thermal expansion effect),whereas the Hadley model scenario also includes consideration of the rise caused by the melting of mountain glaciers. Although melting of the polar ice sheets may contribute to sea level rise in the long-term,neither of the model estimates includes consideration of the changes in sea level caused by the accumulation or melting of snow on Greenland and Antarctica[18]. The global climate models also do not include the local, but significant,component of sea-level change caused by changes in the heights of coastlines as they rise or fall due to regional or even local effects (e.g.,the pumping out of groundwater, earthquakes, isostatic adjustment from the last glacial period,

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[18] In the IPCC 1996 report,the accumulation and melting of Antarctica and Greenland were assumed to balance to give no net contribution to sea level change over the 21st century;more recent studies are finding that some parts of Greenland are melting while others seem to be accreting,and that the global warming at the end of the last glacial period apparently has initiated deterioration of parts of the West Antarctic Ice Sheet. Due to limitations in the observations of these ice sheets,however, projections included here do not include contributions from changes in the size of these polar ice sheets, even though strong warming seems likely to contribute to their melting and thence to sea-level rise.

etc.). Given these caveats, Figure 19 presents the model projections for the estimated rise in global sea level from the two models used in the National Assessment. Over the next hundred years, a rise of sea level of about one and a half feet (about 0.5 meters) is considered likely based on these projections. Maps of the regional pattern of sea-level change around the US are presented in the Coastal chapter, where the effects of local changes in the level of the coastline are also considered. A rise of this amount would be several times as much as occurred during the 20th century. As indicated in the Coastal chapter, even a relatively modest rise can cause extensive coastal erosion (e.g., see Leatherman et al., 2000).

CLIMATE MODEL SCENARIOS OF CHANGES IN CLIMATIC PATTERNS, VARIABILITY, STORMS, AND EXTREMES FOR THE 21st CENTURY

Changes in Climate Patterns, Variability, and Storms

Examination of the patterns of global-scale climate change provides the broader context needed to understand the changes in storm tracks, precipitation belts, and other variations over the US. Such analyses can be undertaken because the simulation of large-scale natural variability by the climate models is generally reasonable (e.g., Stouffer et al., 2000). As for virtually all global models, both models used in the National Assessment project that, in comparison to global average changes, warming at high latitudes will be greater during winter and warming of the land will be greater than of the ocean (Figure 20). The dramatic wintertime warming in high latitudes is very likely due to feedbacks involving the reduction in the reflectivity of the surface as sea ice melts and because weakening of the near-surface inversion allows a relatively large temperature change to occur. Land warms more than ocean because of the oceans' greater ability to limit and redistribute the trapped energy by evaporating moisture, mixing heat downward, transporting heat around by ocean currents, and the ocean's larger heat capacity. In addition, the warming of land areas increases as soil moisture is reduced, which reduces the potential for evaporative cooling. Although not shown in these figures, another robust feature of global warming is greater warming at upper levels of the tropical atmosphere. This warming occurs because of the way that the vertical atmospheric structure is determined through convection and the removal of moisture with altitude. The upper atmosphere warming affects how the atmospheric circulation changes, the generation and intensity of convective rainfall (rainfall resulting from vertical motion in

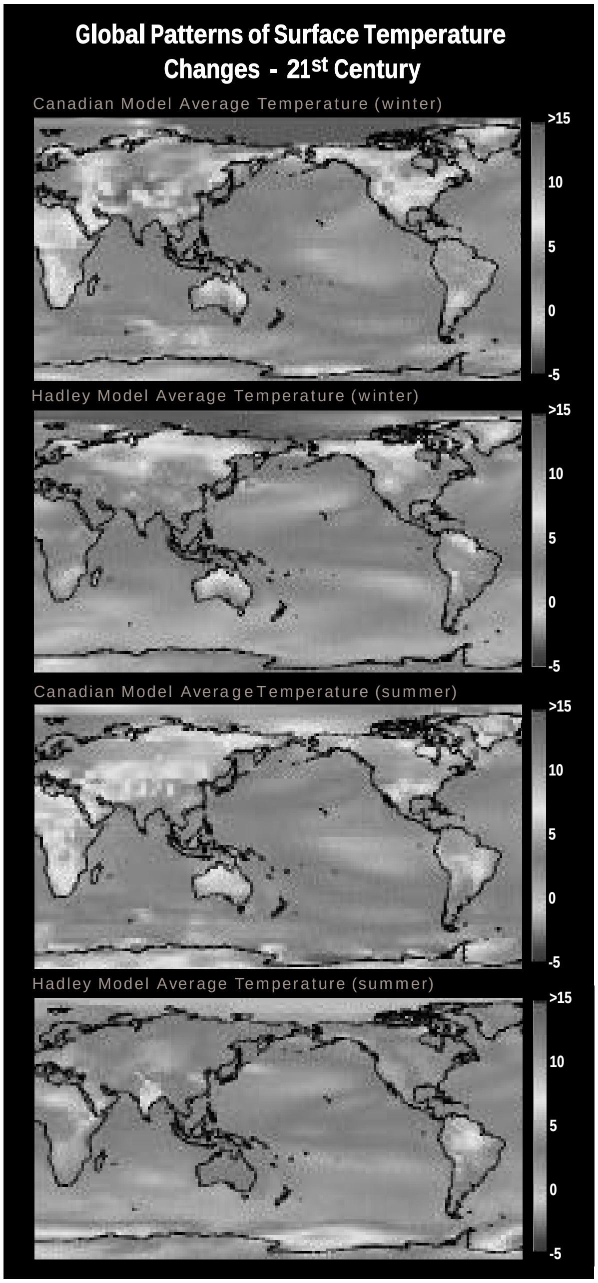
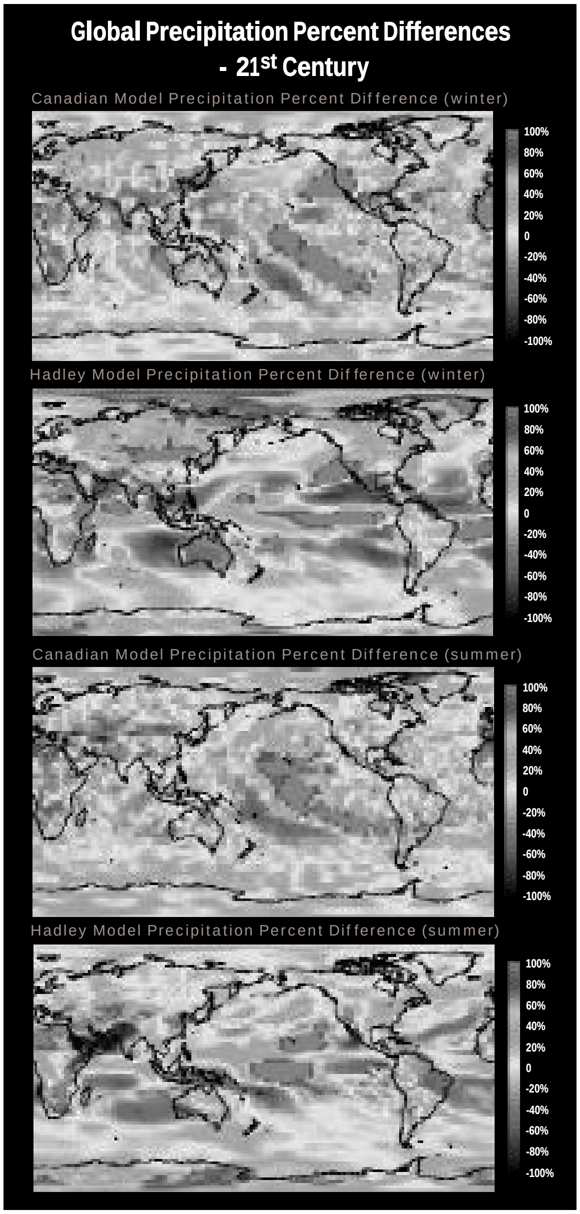


Figure 20: Global patterns of projected changes in surface temperature (˚F) over the 21st century [future (2090-2099) and modern (1961-1990)] for (a) December, January, February (DJF) from the Canadian model scenario, (b) DJF from the Hadley model scenario, (c) June, July, August (JJA) from the Canadian model scenario, and (d) JJA from the Hadley model scenario. See Color Plate Appendix.

the atmosphere),and the development of tropical storms.

Model projected changes in regional temperatures over the Pacific Ocean indicate greater warming over the equatorial and northern East Pacific Ocean, and that these changes extend to the West Coast of the US in both models (Figure 20). This pattern of warming resembles an El Niño pattern of sea surface temperature (SST) anomalies,and so it would seem very likely to lead to an El Niño-like wind and precipitation response. Other models (Meehl et al., 2000b) also show this type of response (Meehl and Washington,1996;Knutson and Manabe,1995,1998; Timmermann et al.,1999),although some models show a La Niña-like (Noda et al.,1999),or an initial La Niña-like,pattern that transitions into an El Niño-like pattern (Cai and Whetton,2000). This response appears to be highly dependent upon how cloud feedbacks are represented by the models,so remains quite uncertain (Meehl et al.,2000b).


Global Precipitation Percent Differences - 21st Century

Canadian Model Precipitation Percent Difference (winter)

Hadley Model Precipitation Percent Difference (winter)

Canadian Model Precipitation Percent Difference (summer)

Hadley Model Precipitation Percent Difference (summer)

Figure 21: Global precipitation percent differences [(future - modern)/modern) x 100] for (a) December, January, February (DJF) from the Canadian model scenario, (b) DJF from the Hadley model scenario, (c) June, July, August (JJA) from the Canadian model scenario, and (d) JJA from the Hadley model scenario. See Color Plate Appendix.

The global precipitation anomalies (Figure 21) projected by the models show increased precipitation coinciding with the region of these warm anomalies. The increased precipitation in the Southwest appears to be largely a result of the warmer SSTs in the Pacific Ocean off the coast of North America. During winter, decreased precipitation along the northern branch of the Hadley Circulation (the atmospheric circulation with rising air near the equator and sinking air near 30˚ latitude, resulting in the trade winds and subtropical dry regions) extends over the eastern US in the Canadian model scenario,but not in the Hadley model scenario. During summer, the Hadley model scenario shows a large area of decreased precipitation in the eastern Pacific and Atlantic Oceans,whereas the Canadian model scenario projects decreased precipitation over land areas. Recent analyses of the 6-hourly data from the Hadley model indicate that the model is accurately reproducing the Southwest monsoon during summer. In a simulation with increased greenhouse gases (although without sulfates),there are indications of a strengthening of the monsoon (Arritt et al.,2000),which correlates with the region of increased summer precipitation in the Southwest.

Because the Northern Hemisphere's atmospheric circulation is more vigorous during winter, examining the winter circulation pattern provides an indication of the causes of these precipitation changes. The polar jet stream is known to be dependent upon both global and local temperature gradients. While the reduced pole-to-equator temperature gradient at the surface suggests a weaker or northward-shifted jet stream,the increased pole-to-equator temperature gradient in the upper troposphere suggests the reverse. The models calculate the relative influence of each factor and provide a result that is a physically and quantitatively consistent representation of how temperatures,winds,and other atmospheric features might change in the future.

As shown in Figure 22,both models project the strengthening and southward shift in the region of maximum upper atmospheric winds in the eastern

Wintertime Changes in Jet Stream and Atmospheric Circulation

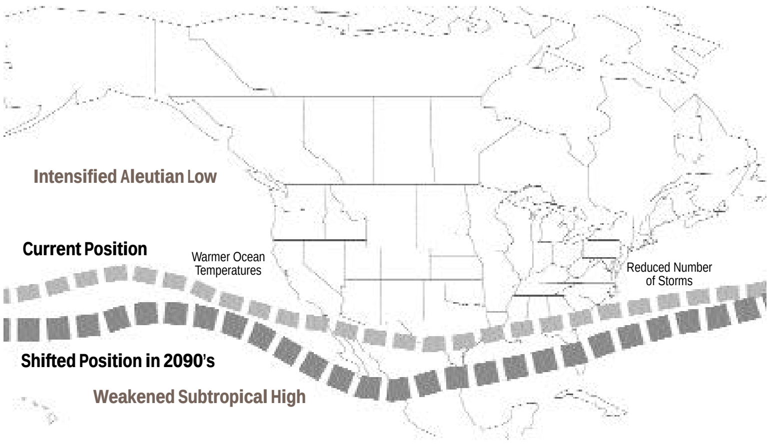


Figure 22: Schematic illustrating wintertime changes in the jet stream, pressure systems, sea surface temperatures, and storm tracks over and adjacent to North America. The Canadian and Hadley model scenarios both show: a southward-shifted jet stream over the eastern Pacific and Southwest; a southward-shifted and intensified Aleutian Low and weakened subtropical High in the West; and warmer ocean surface temperatures off the coast of California. The Canadian model scenario also shows a reduction in the number of storms along the East Coast storm track; however, the Hadley model scenario does not show this reduction nor did it develop this observed storm center in its control simulation. For more details, see Sousounis (1999).

Pacific and across the West Coast (Sousounis,1999; Felzer, 1999). The changes in these winds,which seem in the models to be a combination of the polar and subtropical jets,are indicative of a deepened and southward-shifted Aleutian Low in both models,especially for the Hadley model scenario. The Aleutian Low is a center for storms coming into North America off the Pacific,so a deepening and southward-shift in the Aleutian Low would allow more storms to penetrate further southward towards the California coast,helping to explain the precipitation increases projected for that region. The projected weakening of the Pacific Subtropical High (centered near Hawaii) would reduce upwelling of colder ocean waters,allowing SSTs to rise and enabling more storms to penetrate into the Southwest. Storm counts (Figure 23) confirm that the models are projecting more storms associated with the stronger Aleutian Low. Although the Hadley model scenario shows a slight decrease in storms over the Southwest,there is more moisture in the atmosphere, resulting from the higher SSTs (Felzer and Heard,1999). As a result,the amount of precipitation is actually projected to increase. Other models,however, show reduced storm activity along the Pacific coast (Christoph et al.,1997),so that these results are apparently model dependent.

The region of storm formation off the East Coast of the US is locally dependent upon the land-sea temperature gradient. Warm Gulf Stream waters and a cold land surface in winter provide ideal conditions for generating storms (e.g.,nor'easters). With warming of the land surface,the land-sea contrast is reduced and the intensity of these storms could be reduced. The storms in the Hadley model scenario start in the Mid-Atlantic region and track north and east over the Atlantic Ocean;in contrast,the storms in the Canadian model scenario track closely along the East Coast (Figure 23). Observations indicate that present storm tracks extend along the southeastern coast of the US (Klein,1957),so,in this particular region,the storm tracks are better located in the Canadian model scenario than in the Hadley model scenario,although they are over-represented to the south. Both models project a decrease in the number of storms along this predominant East Coast storm track (Figure 23),although some individual storms appear to be more intense (Felzer and Heard,1999;Carnell and Senior, 1998;Lambert, 1995). Because of the different baseline positions of the storm tracks,however, the effect of the reduced number of storms is felt over the US only in the Canadian model scenario (Felzer and Heard,1999). Note that the increase in the number of storms over East Coast land areas in the Hadley model scenario is probably not statistically significant because there are very few storms there to begin with. A decreasing number of storms would be a change from the historical pattern,which does not show any decrease in East Coast storms over the past 100 years,but instead shows an increase during the 1960s (Hayden,1999). A separate study of the results from the Canadian model also indicates that a higher CO_2 concentration will alter wintertime variability and the behavior of the Arctic Oscillation, affecting primarily the North Atlantic and European regions (Monahan et al.,2000). Other studies show an entire range of possibilities for storm changes in the North Atlantic (Meehl et al.,2000b),including more intense storms (Lunkeit et al.,1996),less intense storms (Beersma et al.,1997),and a shift in storm tracks towards the northeast with no change in intensity (Schubert et al.,1998).

Changes in the tracks of storms and jet streams may also be the result of changes in tropical circulation due to changes in the model projections for the El Niño-Southern Oscillation (ENSO). ENSO is presently a major cause of inter-annual variations in tropical and global circulation. During warm ENSO events (El Niño),the waters in the eastern and central equatorial Pacific Ocean warm, changing the atmos-

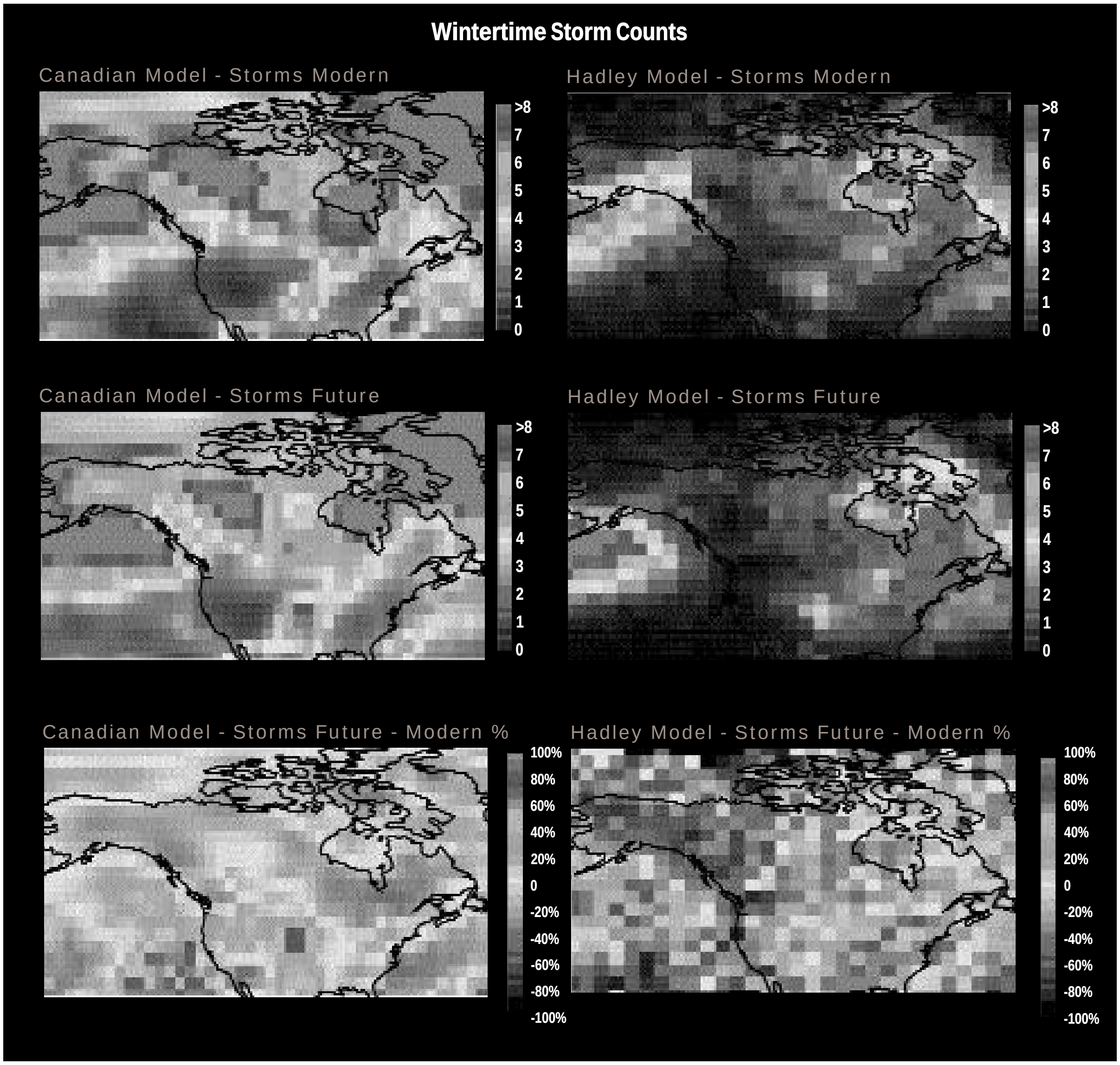


Figure 23: Wintertime (DJF) storm counts (Carnell and Senior, 1998; Lambert, 1995) from the (a) Canadian model scenario (1901-1910 total); (b) Hadley model scenario (1990-2110 mean from unforced control run); (c) Canadian model scenario (2091-2100 total); (d) Hadley model scenario (2070-2100 mean from transient run); (e) Canadian model scenario delta (c-a); and (f) Hadley model scenario delta (d-b). Units are number of winter storms per 145,000 km^2. See Color Plate Appendix.

pheric and oceanic circulations in the Pacific region, which affects global weather patterns and the position of the jet stream over North America. The potential effects of global warming on ENSO are not yet established with confidence, in part because of the limited ability of GCMs to simulate ENSO variations over the 20th century. However, both oceanic and atmospheric indices can be used to provide some indications of the types of changes the models are projecting. In particular, although the findings must be considered uncertain, the Niño SST-based indices and the Southern Oscillation Index (SOI) do provide an indication of how atmospheric pressure patterns may shift.

Indices for the Niño-3 and 4 regions in the Pacific Ocean, which record changes in the SST, show ENSO cycles continuing to occur in both models as the world warms, although around a higher average oceanic temperature (D. Legler and J. O'Brien, personal communication; see http://www.coaps.fsu.edu/~legler/NAST/Assess_ENSO.html). Examining the SOI results, the Canadian model scenario projects a shift towards a more persistent set of conditions that is similar to an El Niño state (He and Barnston, personal communication), while the Hadley model scenario shows no change. In neither case do these models project a significant change in the frequency or amplitude of ENSO variability (Collins, 2000). A recent study using a model with sufficient tropical resolution to more accurately reproduce ENSO variability has shown increased ENSO amplitude (El Niños and La Niñas are both more intense) as a result of greenhouse warming (Timmermann et al., 1999). Other studies (Meehl et al.,2000b),however, show little change (or even a slight reduction) in ENSO amplitude (Knutson et al.,1997),while the Hadley model scenario shows an increase in amplitude only after CO_2 levels have been quadrupled (Collins,2000). Because there are several frequencies of variability within the ENSO signal (Meehl et al.,2000b;Zhang et al.,1997;Lau and Weng,1999; Allan et al.,1996;Knutson et al.,1997),it is often difficult to determine how ENSO is changing, even with a century-long time series. Given these model results,the stronger Aleutian Low and weaker subtropical high (Trenberth and Hurrell,1994) that both Assessment models project over the Pacific seem likely to result from either the El Niño-like response in the two models or from the warm ENSO phase (El Niño) response evident in the Canadian model scenario.

Many of the precipitation changes in the GCMs,particularly during summer when the atmospheric circulation is weaker, appear to be the result of feedbacks involving the land surface. During winter, snow cover is the mechanism for this interaction, while during summer, soil moisture is most important. As warming occurs over land areas, evaporation of available moisture increases and the soil moisture decreases;as the land dries out,this soil moisture leads to a decrease in overall evaporation and therefore of the amount of precipitable water in the atmosphere. This decrease,in turn, results in fewer clouds,less precipitation,and increased warming,completing the positive feedback loop. Thus, while increased warming over the ocean is projected to result in increased precipitation,the increased warming over land is projected to lead to less precipitation because of the limited moisture-holding capacity of the land. Differences in model projections of changes in precipitation over land during summer may therefore result from differences in the respective land surface models used in each GCM. Soil moisture trends generally correlate with precipitation anomalies during winter. Although soil moisture trends (Figure 18) during summer also correlate with the precipitation anomalies,there are even broader areas of decreased soil moisture due to the large increases in evapotranspiration. For example, both models show drying in the western Great Plains during summer. Another example is Alaska, where increases in evaporation due to increased summer temperatures are projected to lead to decreased soil moisture even though precipitation increases (Felzer and Heard,1999).

Snow cover also plays an important role in wintertime changes in climate. Given the degree of warming across the US,the models project that the extent of snow cover is very likely to be significantly reduced (Figure 24). As the snow line retreats poleward,a larger surface area is exposed to a lower albedo surface,which increases the amount of warming,creating a large positive feedback. While both the Canadian and Hadley models show the snowline retreating towards the end of the 21st century, the reduction in snow cover over the US is projected to be particularly dramatic in the Canadian model,where mean wintertime snow cover exists only in the northern Rocky Mountains and northern Great Plains. Although snow cover still remains in

Winter Average Snow Cover Difference - 2090s

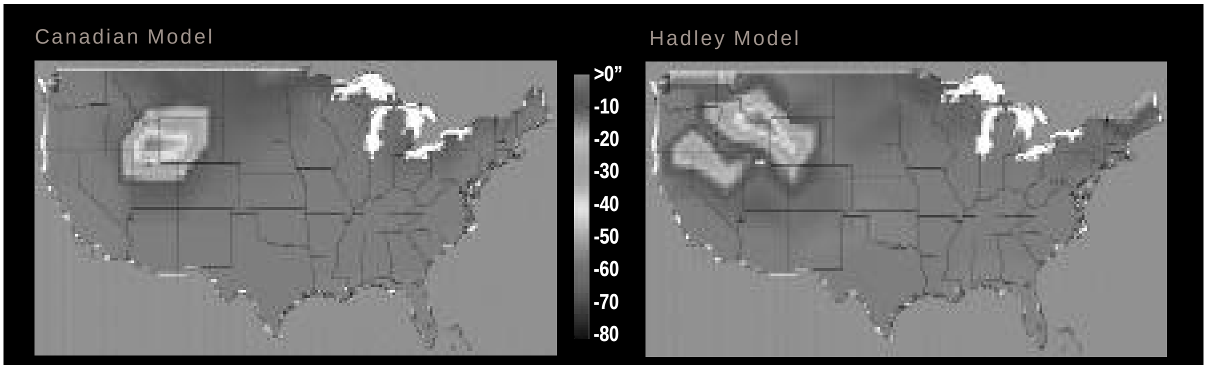
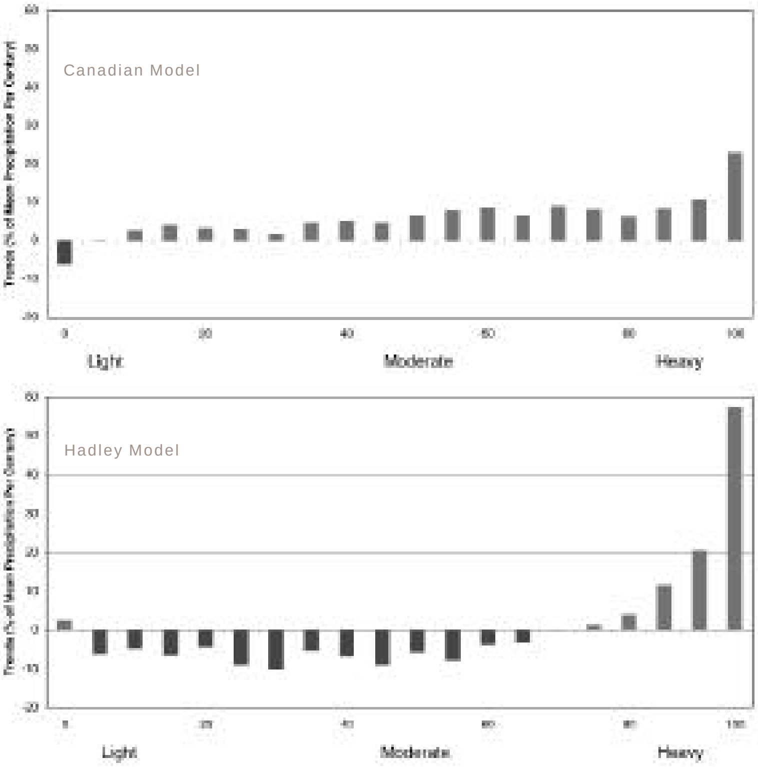


Figure 24: Projections across the US of the decrease in winter average snow accumulation (inches) from 1961-1990 to 2090-2099 based on results from the (a) Canadian model scenario and (b) Hadley model scenario. In these diagrams, the changes in snow depth calculated as differences in the water equivalent of snow in kg/m^2 have been converted to depth of dry snow (in inches), assuming a 15 to 1 average ratio of snow depth to water equivalent (Judson and Doesken, 2000). See Color Plate Appendix.



Projected Changes in Intensity of National Daily Precipitation

Figure 25: Bar chart showing projected changes in frequency of various types of precipitation. Both the (a) Canadian and (b) Hadley model scenarios project increases in the frequency of heavy precipitation events, intensifying the trend observed for the 20th century. Figure prepared by Byron Gleason of the National Climatic Data Center based on the methods described in Karl and Knight (1998).

the northern Rocky Mountains, both models project that the amount of snow in this region will be dramatically reduced. The sharply reduced extent of snow cover in the Canadian model scenario, which may have been initiated by the more zonal flow conditions leading to higher wintertime temperatures and fewer outbreaks of Arctic storms, allows more absorption of solar radiation, especially early in the year. This effect further diminishes snow cover and increases the warming in the Canadian model simulation.

Climate Extremes

While changes in average conditions and inter-annual variability are expected to have significant effects for some ecosystems and some parts of the economy, other parts of the economy are projected to be affected more by potential changes in the frequency or intensity of extreme events. It is likely that the frequency of occurrence of exceeding certain thresholds and the intensity of extreme events might change because temperatures and absolute humidity are projected to increase, as is the hydrologic cycle of evaporation and precipitation. Many models project a greater frequency of extreme high temperatures and decrease in frequency of extreme low temperatures as a result of increased greenhouse gas concentrations (Giorgi et al., 1998; Meehl et al., 2000b). Increased daily temperature variability in summer and decreased daily temperature variability in winter is also likely (Mearns et al., 1995; Gregory and Mitchell, 1995; Zwiers and Kharin, 1998; Meehl et al., 2000b). As observed (Karl and Knight, 1998) and modeled (Meehl et al., 2000b), reduced diurnal temperature range may result from a greater increase in minimum temperatures than maximum temperatures. Both observations (Gaffen and Ross, 1998) and model results (Delworth et al., 1999), including the current scenarios (Figure 15), show an increase in the heat index, which is a measure of the discomfort level due to warming.

Trends in one-day and multi-day precipitation events over the US and other countries show an increase in the number of days with the heaviest amounts of precipitation (Karl and Knight, 1997, 1998). The number of days annually with precipitation exceeding 2 inches (about 5 cm) has been increasing in the US (Karl et al., 1995a) and the frequency of the highest 1- to 7-day precipitation totals has also been increasing (Kunkel et al., 1999). Increases have been largest for the Southwest, Midwest, and Great Lakes regions of the US. Projections from the Hadley and Canadian model scenarios show an increase of heavy precipitation events as the climate warms (Figure 25). Hulme et al. (1998) found some agreement between the projected precipitation changes and recently observed trends. In reviewing the Canadian model results, Zwiers and Kharin (1998) found that extreme temperature and precipitation events are very likely to occur more frequently. Many other modeling studies also show an increase in the heaviest precipitation events (Meehl et al., 2000b; Kothavala, 1997; Hennessy et al., 1997; Durman et al., 2000; Giorgi et al., 1998). Studies on changes in climate extremes are summarized in recent workshop proceedings (Karl and Easterling, 1999; AGCI, 1999; Easterling et al., 2000b) and in Meehl et al. (2000b). Summer drying in mid-continental regions due to increased evaporation, sometimes coupled with decreased precipitation, has also been projected in many models (Haywood et al., 1997; Gregory et al., 1997; Wetherald and Manabe, 1999; Meehl et al., 2000b).

Studies with the GFDL hurricane model (Knutson et al., 1998; Knutson and Tuleya, 1999) also suggest that the rate of precipitation during tropical storms could increase due to the warmer conditions and the increased amount of water vapor in the atmosphere. Other studies confirm these results (Krishnamurti et al.,1998;Walsh and Ryan,1999; Meehl et al.,2000b). Two additional studies show a decrease in the frequency of hurricanes as a result of global warming (Bengtsson et al.,1996; Yoshimura et al.,1999). Both the Canadian and Hadley model scenarios project an increase of heavy precipitation events as the climate warms. Ultimately there is a strong dependence of hurricanes on ENSO (Meehl et al.,2000b;Knutson et al., 1998;Knutson and Tuleya,1999),indicating that how ENSO changes is likely to be an important indicator of how hurricanes will vary, especially for the southeastern US.

Precipitation is the driving factor affecting streamflow (Langbein,1949;Karl and Reibsame,1989) so the observed and projected increase in the intensity and frequency of heavy (the upper 5% percentiles of all precipitation events) and extreme precipitation (the highest annual 1-day precipitation events) have the potential to increase inland flooding. Higher temperatures,conversely, have the potential for exacerbating drying of the soil and, over time,of increasing drought frequency and intensity. Separating these two influences is challenging. Nonetheless,analyses of changes in drought frequency and intensity (Karl et al.,1995a) reveal no trend in drought frequency, but they do reveal an increase in the area affected by severe and extreme moisture surplus. Streamflow data analyzed by Lins and Slack (1999) also reveal an increase in low-stream flows,adding more confidence to the notion that drought frequency and intensity has not become more severe,despite the increase in US average temperature. On the other hand,Lins and Slack (1999) do not find an unusual number of statistically significant increases of streamflow, despite the fact that Karl and Knight (1998) show statistically significant increases of precipitation,including heavy and extreme events. New analyses indicate a strong relation between multi-decadal increases in heavy and extreme precipitation events and high and low streamflows,but with considerable variability (Groisman et al.,1999, 2000). These results indicate that part of this variability is related to reductions in snow cover extent in the West,which have modified the peak stream flows and ameliorated the effect of increased heavy precipitation. In these results,Groisman et al. (2000) find that,when averaged across watersheds and across the country, a clear relationship between heavy precipitation and high streamflow events emerges.

THE CLIMATIC EFFECTS OF STABILIZING THE CARBON DIOXIDE CONCENTRATION

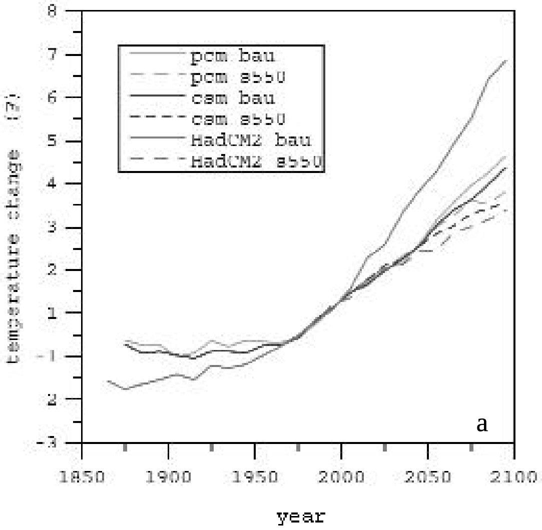
The objective of the Framework Convention on Climate Change (FCCC),of which over 160 countries including the US are signatories,is to stabilize the atmospheric concentration of greenhouse gases "at a level that would prevent dangerous anthropogenic interference with the climate system." Precise goals for stabilization of the CO_2 concentration have not been established. To provide information for the negotiating process,the IPCC considered stabilization at concentrations of 350,450,550, 650,750,and 1000 ppmv, plus a variety of temporal pathways to reach these goals (Wigley et al.,1997). Many alternative carbon emission and CO_2 concentration pathways have been evaluated for achieving stabilization at 550 ppmv, which represents an approximate doubling of the pre-industrial CO_2 concentration. Different end points and emission pathways arise from different assumptions about the speed at which emissions can or will be reduced based on views about feasibility or optimality of policies,measures,and technological changes.

To provide an estimate of the reduction in climate change that might occur with CO_2 stabilization,the NAST asked the National Center for Atmospheric Research (NCAR) to use new models to carry out special simulations to provide an indication of the size of the climatic change that would result from stabilizing the CO_2 concentration. NAST and NCAR scientists chose to examine the climatic consequences of a reduced emission growth scenario involving eventual stabilization at 550 ppmv. This emissions path would allow continued growth in emissions for a few decades into the 21st century, followed by rapid decreases in emissions. While this emission path is a plausible alternative for investigation of potential climatic impacts,it should not be interpreted as the only way to achieve stabilization, as a prediction of what is most likely to happen,or as a preferred policy alternative. Reductions in the projected warming would be greater from scenarios that begin reducing emissions earlier in the 21st century than is assumed in the stabilization scenario used here.

To carry out these simulations,two different climate models were used (Boville and Gent,1998; Washington et al.,2000). Having the results of only one modeling group (albeit with two similar models) is somewhat limiting,especially because the baseline simulation reported here was not the same baseline used in the Canadian and Hadley model scenarios. However, these calculations do provide interesting insights[19]. Similar stabilization runs have now also been completed by the Hadley Centre (Mitchell et al.,2000).

While most of the differences in climatic conditions that would result from moving toward stabilization would occur in the 22nd century, modest effects do become apparent in the latter half of the 21st century (or could occur earlier if earlier actions are taken to reduce the rate of rise of emissions). As indicated in Figure 26,if the emissions pathways were to occur as projected,global and US average temperatures would likely continue to rise significantly during the 21st century, even if actions were taken starting in the near future to limit the growth of emissions in order to move toward stabilizing atmospheric concentrations at 550 ppmv[20]. Basically, the NCAR results (Dai et al.,2001) suggest that, even if such actions are taken,the warming in 2100 would still likely be several degrees Fahrenheit (and other more responsive models would suggest even more). With movement toward stabilization,the warming is projected to be about half a degree Fahrenheit less (or about 10-15% lower) in 2100 than for the "no climate policy"scenario used in the Hadley and Canadian models used in the Assessment. Figure 27 shows the effects of the move toward stabilization on temperature and precipitation patterns over the US. In these model simulations (and other simulations may give different effects),the emissions cutback begins to reduce the warming across the southern US and to change the resulting precipitation pattern slightly.

Global Mean Temperature Anomolies



US Mean Temperature Anomolies

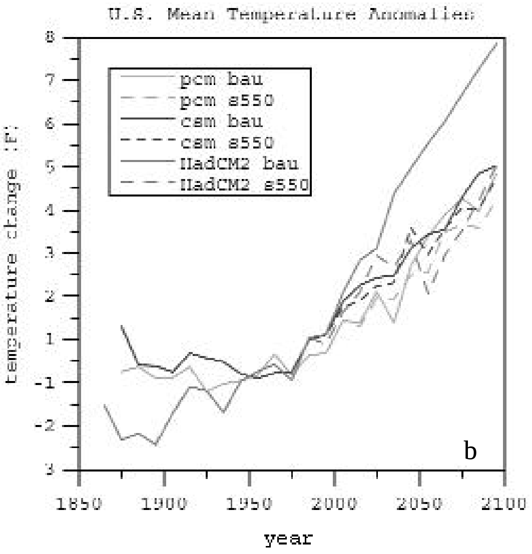


Figure 26: Comparison of the time history of the increase in annual-average surface temperature for (a) the globe and (b) the US as projected by two related models developed at the National Center for Atmospheric Research for an emission scenario where the greenhouse gas concentrations are allowed to rise without restriction (baseline) and for a case (stabilization) where steps are taken to limit the rise in the CO_2 concentration to 550 ppmv (Dai et al., 1999; Washington et al., 2000). Results are also shown for a recent Hadley model simulation (Mitchell et al., 2000). See Color Plate Appendix.

It should also be noted that the reduction in the rate of rise of the CO_2 concentration itself would also have important effects. For forests and agriculture,increased CO_2 stimulates growth and improves water use efficiency under a range of conditions,so that a lesser rise in the CO_2 concentration would likely reduce the increase in crop production and growth of natural biomass (see chapters on Agriculture and Forests) as well as reduce climatic stress on the various ecosystems. For coral reefs, the acidifying effects of CO_2 cause reduced alkalinity of ocean waters, reducing calcification and weakening corals;therefore,limiting the rate of CO_2 increase would help to ameliorate this situation (see Coastal chapter and Kleypas et al.,1999).

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

While much has been learned about the types of climate changes that could occur over the 21st century as atmospheric concentrations of CO_2 increase, much remains to be learned,especially about how the variability and extremes of the climate will change. Although the similarities in how the

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[19] Detailed results from these model simulations are available at http://www.nacc.usgcrp.gov/scenarios/.

Canadian and Hadley models represent changes in global scale features are encouraging, the differences between their results on regional scales suggest that significant uncertainties remain. For example, even though the Canadian model scenario produces a reasonable response to El Niño occurrences across North America, problems with the way these GCMs simulate ENSO variability suggest that the projected pattern of changes may not be definitive. Also, as illustrated by the different projections of changes in summer precipitation in the Southeast, there are often several processes that contribute to the pattern of change that is seen, and these may progress differently. As illustrated by the discussion about changes in storm tracks, often the same process can lead to different projections of changes when imposed on a slightly different base state of the climate. In addition, the different representations of land surface processes (as well as other parameterizations) included in different GCMs can have an important impact on projections of changes in regional precipitation. This dependence occurs because precipitation, unlike atmospheric dynamics, is a highly localized feature of the climate, depending on the interaction of many processes, some of which are still represented in quite schematic ways. Given these many limitations, it is important to mention again that the model projections are not predictions, but that they instead should be viewed as internally consistent scenarios of climatic changes that might occur over the 21st century. As a result, they can, as indicated earlier, only provide indications of the types of consequences that might result.

To build confidence in the projections, much remains to be done. Further improvements in climate models are needed, especially in the representations of clouds, aerosols (and their interactions with clouds), sea ice, hydrology, ocean currents, regional orography, and land surface characteristics. Improving projections of the potential changes in atmospheric concentrations of greenhouse gases and aerosols is underway under the auspices of the IPCC (IPCC, 2000) and model simulations based on these revised emissions forecasts are expected to provide improved estimates of future change. In addition to having results from more models avail-

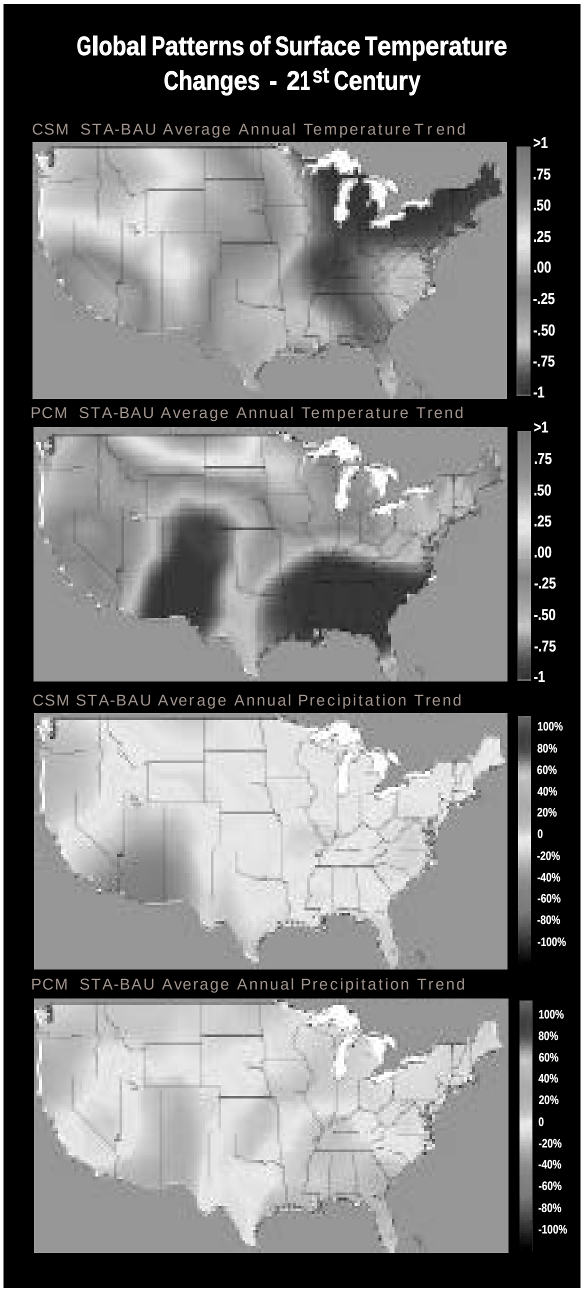

Figure 27: Patterns across the US of projected changes in the trends of annual mean surface temperature and precipitation for the 21st century assuming an emissions profile that moves toward stabilization of the CO_2 concentration at 550 ppmv in the 22nd century (STA) as compared to the baseline case (roughly case IS92a, or BAU, except projections in sulfur emissions are reduced in the CSM scenario). The projected differences in the changes that would generally be projected (case STA minus BAU) are based on results from: (a) NCAR CSM for annual mean temperature; (b) PCM for annual mean temperature: (c) NCAR CSM annual average monthly precipitation; and (d) PCM annual average monthly precipitation. Temperature trend differences are given as ˚F per 100 years. Precipitation trend differences are given in percent, with both trends calculated using a 1980-1999 baseline. Trends are derived based on a linear regression through each grid point. Results are described in Dai et al. (1999) and Washington et al. (2000). See Color Plate Appendix.

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[20] Stabilizing the atmospheric CO_2 concentration at 550 ppmv over the 21st century would require keeping global average per capita emissions of CO_2 at roughly their present level of 1 tonne of carbon per year as global population increases by about 50% and developing nations raise their energy levels to enhance their standard-of-living. Accomplishing this would require that all energy needs for the growing population would have to be met by an appropriate combination of reducing CO_2 emissions (e.g., through higher efficiencies, use of less carbon intensive fuels, etc.), switching to energy sources not based on fossil fuels (e.g., wind, solar, hydro, biomass, nuclear, etc.), providing more efficient energy services, or reducing the emissions of other greenhouse gases.

able,ensembles of simulations from several model runs are needed so that the statistical significance of the projections can be more fully examined. As part of these efforts,it is important to develop greater understanding of how the climate system works (e.g.,of the role of atmosphere-ocean interactions and cloud feedbacks),to refine model resolution,to more completely incorporate existing knowledge into climate models,to more thoroughly test model improvements,and to augment computational and personnel resources in order to conduct and fully analyze a wider variety of model simulations,including mesoscale modeling studies.

While much remains to be done that will take significant time, much can also be done at present to improve the use and understanding of potential climate change scenarios. For example,an intensified analysis program is needed to provide greater understanding of the changes and the reasons they occur. New efforts to examine the synoptic patterns of the changes in the global models were started at the national level in the analyses presented here. Such effort are also starting through region-specific studies that combine analysis of the model results with the insights available from analysis of historical climatology and past weather patterns (i.e.,synoptic conditions). For example,Risbey et al.(1999) have constructed regional climate scenarios for two study regions in North America (Chesapeake Bay and Oklahoma/Great Plains) using a combination of GCM output and dynamical reasoning. Other approaches being pursued involve use of mesoscale models that provide higher resolution of spatial conditions even though they can only provide simulations of shorter periods of time and smaller spatial scales.

SUMMARY

There are clear indications that the atmospheric concentrations of CO_2 and other greenhouse gases and aerosols are being increased by human activities. These changes in atmospheric composition, combined with the influences of other natural and human-induced changes,are changing the climate. Available model simulations,combined with our understanding of the factors that have changed the Earth's climate in the past,provide clear evidence that global warming is occurring and that additional warming will result. There is clear evidence on the global scale that this warming is occurring,with the warming during the 20th century in reasonable accord with model simulations. Because climate affects the environment and many of our natural resources,considering how such changes might affect us will provide important information on how we will need to adapt to such changes.
Use of historical climate data provides one basis for exploring the environment and society's vulnerability to a changing climate. Records of the US climate indicate that the climate is apparently starting to change in a manner consistent with the observed global-scale changes. These records also indicate that there have been significant variations in the climate,which have in turn had important effects on agriculture, water resources,and public health. There is no reason to believe from the historical or paleoclimatic record or from model results that such changes will not recur in the future. To help in analyzing societal vulnerability to ongoing climate variations,a range of historical information about the climate of the 20th century has been provided for the Assessment.

To explore how future climate may be affected by the rising concentrations of greenhouse gases, model simulations have been used to provide quantitative estimates. Although emission scenarios are uncertain and model simulations are still imperfect (e.g.,due to limitations in the representations of important processes and feedbacks),two sets of model results have been assembled to provide plausible projections of how conditions may change over the US during the 21st century. These models project quite significant warming across the US and substantial stress on water resources in several regions. While the particular sets of model results do not fully bound all of the possible futures,they do provide a range of possible future conditions that can be used to start to explore the potential consequences of climate change for the US.

The results available for this Assessment thus provide the basis for the most complete analysis yet undertaken and point to pathways for future analysis and research. Current understanding clearly indicates that the climate is changing and is very likely to change significantly more in the future. At the same time, much more work is needed over the coming years to improve global and mesoscale projections of future changes in CO_2 concentration and of climate,to improve simulation of climate variability, to develop the means to project changes in extreme events,and to expand the statistical analysis and interpretation of existing and planned model simulations. Practical efforts should continue at the community level to interpret the scientific data and climate scenarios with the aim of providing usable information that integrates current needs with planning for future community development.

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