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The Potential Effects Of Global Climate Change On The United States

THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES

REPORT TO CONGRESS

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FOREWORD

I am pleased to transmit the attached *Report to Congress: The Potential Effects of Global Climate Change on the United States.* This report, written in response to a congressional request in the Fiscal Year 1987 Continuing Resolution Authority to prepare two reports on climate change, focuses on the health and environmental effects of climate change. A second draft report, Policy *Options for Stabilizing Global Climate,* is being revised in preparation for delivery to Congress.

This report is one of the most comprehensive published studies of the potential impacts of the greenhouse effect. It examines national effects and, more specifically, impacts on four regions of the United States: California, the Great Lakes, the Southeast, and the Great Plains. Fifty studies conducted by government, academic, and consulting scientists to examine impacts are included. EPA provided common scenarios of climate change to the scientists for use in their analyses. This report is an overview of the results of those studies.

I invite you to carefully read the Executive Summary and the chapters that follow. Although it is difficult to summarize such a large and comprehensive project in a few words, it is fair to say that climate change could lead to significant changes in many ecological and socioeconomic systems. The environmental impacts of a relatively rapid climate change may be particularly acute. Sea level rise could lead to the loss of many coastal wetlands, while a rapid warming could reduce the populations of many plants and animals and, in some cases, lead to extinction of species.

The socioeconomic effects, especially on a regional scale, also may be quite important. Significant expenditures may be needed for such measures as protecting areas from sea level rise, building dams and reservoirs for flood and drought protection, modifying infrastructure, and adding electricity capacity.

I urge caution in interpreting the results of these studies. Since we cannot predict regional climate change or extreme events such as hurricanes or droughts, we cannot predict impacts. The work done for this study was based on scenarios of climate change and is indicative of what could occur in the future. So, too, this work does not identify all of the impacts of climate change, the interactions, or the economic damages that could result.

In examining a study such as this, there is often a temptation to identify "winners" and "losers." One must be careful in drawing such conclusions. The scenarios are based on a certain point in time (when carbon dioxide levels have doubled); and they assume that climate stops changing. If emissions are not stabilized, climate change will not stop at this carbon dioxide doubling, but will continue to warm. With continued warming, what was a positive effect could become negative. Responding to climate change would be a matter of keeping up with increasing rates of change.

I feel this report is a significant contribution to our understanding of climate change impacts. More work needs to be done on understanding impacts on other systems and regions. Yet, this information will be helpful as we address the difficult problems associated with climate change.

Terry Davies
Assistant Administrator
Office of Policy, Planning and Evaluation

ACKNOWLEDGMENTS

This report was made possible because of the hundreds of people who participated in workshops, conducted research projects, reviewed draft manuscripts, and contributed ideas that shaped the final product. They shared a common belief that an objective analysis of global climate change could be undertaken despite the uncertainties in scientific information. We are grateful for their support and encouragement. It was the difference that sustained us through this effort. In particular, we wish to acknowledge the authors who organized and integrated the following chapters.

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Chapter 18: Research Needs	Anthony Janetos
Chapter 19: Preparing for Climate Change	James G. Titus

Special thanks are extended to Roy Jenne of the National Center for Atmospheric Research. Mr. Jenne and Dennis Joseph of his staff collected data from the GCMs and assembled them in a way that could be easily used by the effects researchers. In addition, he collected historic weather data for 1951-80 and distributed them to the researchers as needed.

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EXECUTIVE SUMMARY

Scientific theory suggests that the addition of greenhouse gases to the atmosphere will alter global climate, increasing temperatures and changing rainfall and other weather patterns. In 1979, the National Academy of Sciences estimated the most probable global warming from a doubling of carbon dioxide concentrations over preindustrial levels to be between 1.5 and 4.5°C. In 1985, the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), and the International Council of Scientific Unions (ICSU) reaffirmed these estimates. Such a climate change could have significant implications for mankind and the environment: it could raise sea level, alter patterns of water availability, and affect agriculture and global ecosystems.

Although there is consensus that increased greenhouse gas concentrations will change global climate, the rate and magnitude of change are not certain (see box entitled "Climate Change"). Uncertainties about climate feedbacks from clouds, vegetation, and other factors make it difficult to predict the exact amount of warming that a given level of greenhouse gases, such as doubled carbon dioxide (CO_2) concentrations, would cause. How quickly climate may change also is not known, because scientists are uncertain both about how rapidly heat will be taken up by the oceans and about some climate feedback processes. Generally, scientists assume that current trends in emissions will continue and that climate will change gradually over the next century, although at a much faster pace than historically. At this rate, the full effect of the equivalent doubling of CO_2 concentrations probably would not be experience until after 2050. It is possible, however, that sudden changes in ocean circulation could cause abrupt changes in global climate. Indeed, if climate changed more rapidly than estimated, adapting to the effects would be more difficult and more costly. Furthermore, continued emissions of greenhouse gases could raise atmospheric concentrations beyond doubled CO_2 causing greater and more rapid climate changes, and larger effects.

To explore the implications of climate change and ways to control it, Congress asked the U.S. Environmental Protection Agency (EPA) to undertake two studies on the greenhouse effect: the first study was to address "The potential health and environmental effects of climate change including, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, estuaries as well as societal impacts;" and the second study was to examine "policy options that if implemented would stabilize current levels of greenhouse gas concentrations." The second study, "Policy Options for Stabilizing Global Climate," is a companion report to this document.

EPA responded to this request by first holding workshops with atmospheric scientists to discuss the use of global climate change models for impact analyses and then meeting with ecologists, hydrologists, geographers, and forestry and agricultural specialists to identify topics for this study. A major purpose was to bridge the gap in our ability to relate a rise in average annual surface temperatures to regional climate changes. Based on these and other discussions, EPA decided to use common scenarios of climate change to analyze the sensitivities of coastal resources, water resources, agriculture, forests, biodiversity, health, air pollution, and electricity demand to climate change on regional and national scales (see Figure 1). These systems were chosen for analysis because they are sensitive to climate and significantly affect our quality of life. EPA decided to conduct regional analyses for the Southeast, the Great Plains, California, and the Great Lakes, because of their climatological, ecological, hydrological, and economic diversity. Leading academic and government scientists in the relevant fields used published models to estimate the impacts on both the regional and national scales. As a common base for conducting these analyses, they used the scenarios specified by EPA.

After consulting with scientific experts, EPA developed scenarios for use in effects analysis. Regional data from atmospheric models known as General Circulation Models (GCMs) were used as a basis for climate change scenarios (see box on “Scenarios and Methodology”). The GCMs are large models of the ocean-atmosphere system that simulate the fundamental physical relationships in the system. GCMs provide the best scientific estimates of the impacts of increased greenhouse gas concentrations on climate. Yet, they use relatively simple models of oceans and clouds, both of which will be very critical in influencing climate change. The GCMs generally agree concerning global and

CLIMATE CHANGE

A panel of experts convened by the National Academy of Sciences (National Research Council, 1987) recently gave the following estimates of scientific confidence in predictions of the climate response to increased greenhouse gas concentrations. This table summarizes only their conclusions concerning “the possible climate responses to increased greenhouse gases.” The full report should be consulted for the details.

Large Stratospheric Cooling (virtually certain). The combination of increased cooling by additional CO_2 and other trace gases, and reduced heating by reduced ozone “will lead to a major lowering of temperatures in the upper stratosphere.”

Global-Mean Surface Warming (very probable). For an equivalent doubling: of CO_2, “the long-term global-mean surface warming is expected to be in the range 1.5 to 4.5°C.”

Global-Mean Precipitation Increase (very probable). “Increased heating of the [Earth's] surface will lead to increased evaporation and, therefore, to greater global mean precipitation.” Despite this increase in global average precipitation, some individual regions might well experience decreases in rainfall.”

Reduction of Sea Ice (very probable). This will be-due to melting as the climate warms.

Polar Winter Surface Warming (very probable). Due to the sea ice reduction, polar surface air may warm by as much as 3 times the global average.

Summer Continental Dryness/Warming (likely in the long term). Found in several, but not all, studies, it is mainly caused by earlier termination of winter storms. “ Of course these simulations of long-term equilibrium conditions may not offer a reliable guide to trends over the next few decades of changing atmospheric composition and changing climate.”

Rise in Global Mean Sea Level (probable). This will be due to thermal expansion of seawater and melting or calving of land ice.

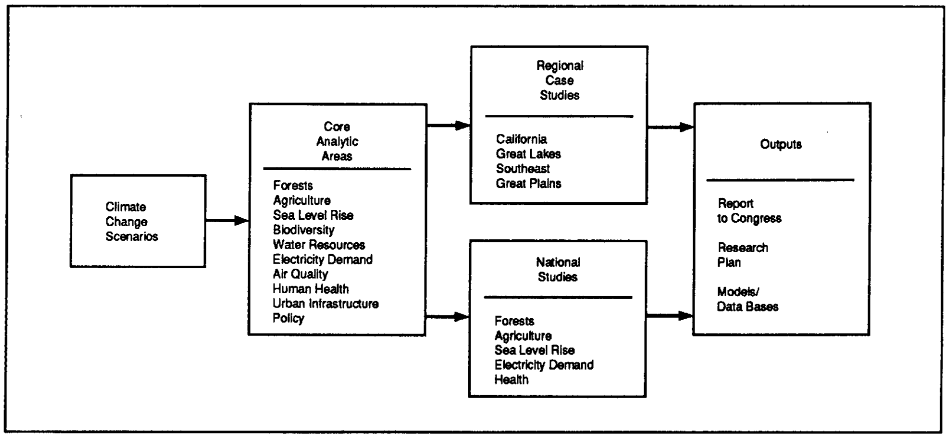


Figure 1. Elements of the effects report.

SCENARIOS AND METHODOLOGY

A number of scenarios were specified by EPA to help identify the sensitivities of natural and manmade systems of climate change. Scenarios were used as inputs with models of natural resources. Most researchers used GCM-based scenarios. Some used analog scenarios or expert judgement.

Regional outputs from three General Circulation Models (GCMs) were used: the Goddard Institute for Space Studies (GISS); the Geophysical Fluid Dynamics Laboratory (GFDL); and Oregon State University (OSU). All of these models estimate climate change caused by a doubling of CO_2 concentrations in the atmosphere. The regional estimates of doubled CO_2 changes were combined with 1951-80 climate observations to create doubled CO_2 scenarios. The GISS model has been used to estimate how climate may change between now and the middle of the next century. This is called a transient run, the outputs of which were used to create a transient scenario.

Other approaches were used to supplement the GCMs. Weather observations from the 1930s were used as an analog for global warming, although greenhouse warming may raise temperatures much higher than they were in that decade. In some cases, paleoclimatic warmings were studied to provide evidence of how species respond to climate change. In addition, the use of scenarios were supplemented by expert judgement (gathered though literature reviews and workshops with scientific experts) to provide the best opinions on potential effects.

Since we cannot predict the exact nature of climate change, we cannot predict its impacts. All these analytic approaches help us to determine the potential sensitivities and vulnerabilities of systems to climatic change.

latitudinal increases in temperature, but they disagree and are less reliable concerning other areas, such as regional changes in rainfall and soil moisture. The GCM data were compared with historic meteorologic data. In addition, the decade of the 1930s was used as an analog for global warming.

In Figure 2, the temperature changes from the three GCMs used to create scenarios are shown for both the United States and four regions of the United States for a doubling of carbon dioxide levels. The GCMs agree on the direction of temperature changes, but differ in the magnitude. Estimates of precipitation changes are shown in Figure 3. The GCMs agree that annual rainfall would increase across the country, but disagree about the direction of regional and seasonal changes. All models show increased evaporation.

The GCM results should not be considered as predictions, but as plausible scenarios of future climate change. Ideally, one would like to use many regional climate change scenarios to reflect the potential range of climate change. Resource constraints allowed us to use only a limited number of regional climate scenarios. It would also be useful to estimate the probabilities of occurrence for each scenario. Given the state of knowledge, it is difficult to assign probabilities to regional climate change. Because the regional estimates of climate change by GCMs vary considerably, the scenarios provide a range of possible changes in climate for use in identifying the relative sensitivities of systems to higher temperatures and sea level rise. Hence, the results of the studies should not be considered as predictions, but as indications of the impacts that could occur as a result of global warming.

There are two other major limitations in the GCM scenarios. First, the scenarios assume that climate variability does not change from recent decades. Second, the scenarios did not change the frequency of events, such as heat waves, storms, hurricanes, and droughts in various regions, which would have affected the results presented in this report (see "Limitations" box). Changes in variability as estimated by GCMs were examined for this report. We found that no firm conclusions can be drawn about how global warming could affect variability.

The methods used to estimate impacts (for example, how forests might change) also have limitations because our scientific understanding of physiological processes is limited and subject to uncertainties. We have no experience with the rapid warming of 1.5 to 4.5°C

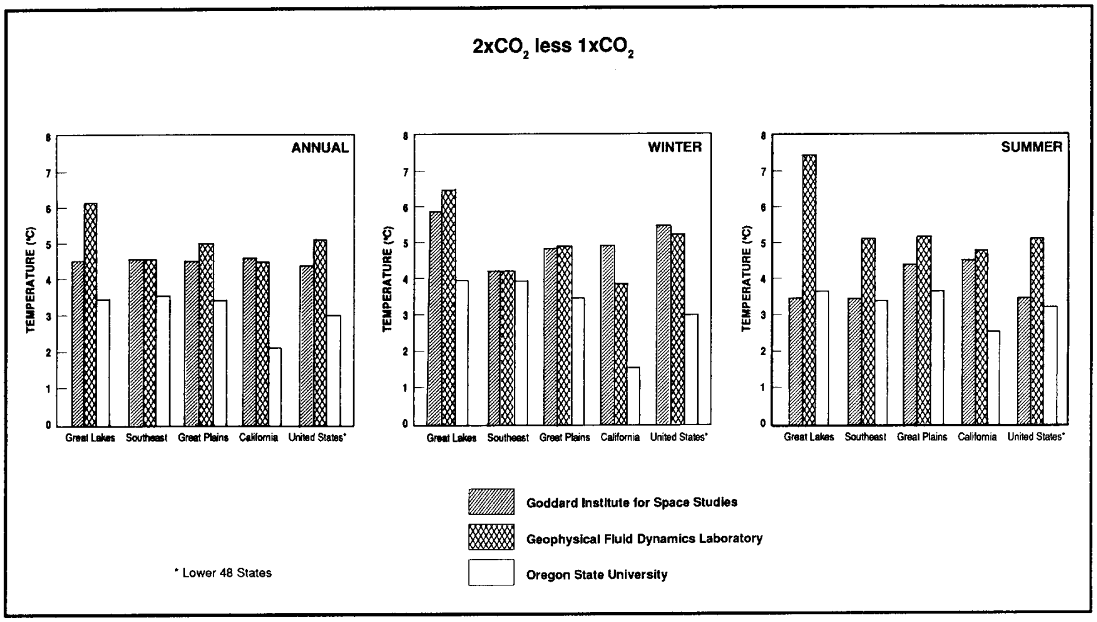


Figure 2. Temperature scenarios.

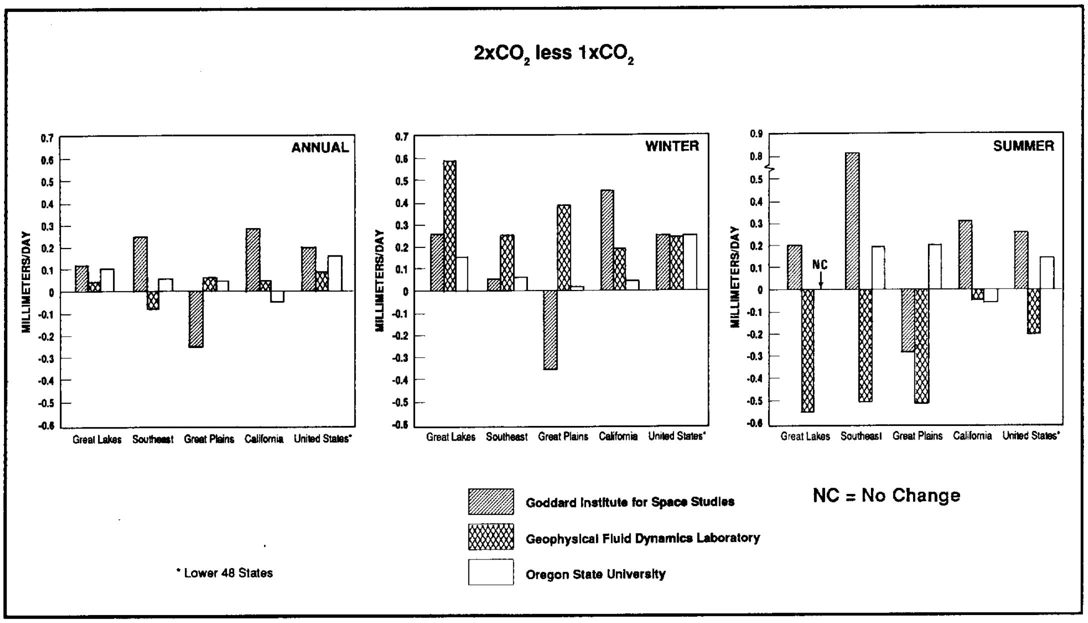


Figure 3. Precipitation scenarios

LIMITATIONS

- Climate Scenarios
  - Differences Between Scenarios. The GCM and other scenarios do not provide for consistent estimates of climate change.
  - Variability. The scenarios assume no change in variability.
  - Major Climate Events. The scenarios assume no changes in hurricanes, droughts, etc.
- Societal Changes. Most studies did not consider changes in population, technology, and other areas. There as only limited consideration of responses and adaptation measures, which could mitigate some of the results presented here.
- Linkages. Many indirect effects (e.g., effect of increased irrigation demand on water resources) were not qualitatively analyzed.
- Limited Effects Analyses. Many effects and regions in the United States were not analyzed. In addition, this report did not analyze the impacts of climate change on other countries. Compared to the United States, it may be much more difficult for poorer and less mobile societies to respond to climate change. It is not unreasonable to assume that climate change could have important geopolitical consequences, which could have subsequent impacts on the United States.
- Effects Analyses. These models were calibrated for historic climate conditions and may not accurately estimate future responses to climate change.

projected to occur during the next century. Many of the effects are estimated based on knowledge of the response of systems to known climate conditions. We cannot be certain that a forest would be able to migrate, how higher atmospheric concentrations of CO_2 would affect vegetation, whether fish would find new habitats, how agricultural pests would proliferate, or how impacts would combine to create or reduce stress.

With some exceptions, we did not generally examine human responses and adaptations to effects of climate change. The report was intended to examine sensitivities and potential vulnerabilities of current systems to climate change. Many other changes will also take place in the world at the same time that global climate is changing. We cannot anticipate how changing technology, scientific advances, urban growth, and changing demographics will affect the world of the next century. These changes and many others may singularly, or in combination, exacerbate or ameliorate the impacts of global climate change on society.

The results are also inherently limited by our imaginations. Until a severe event occurs, such as the drought of 1988, we fail to recognize the close links between our society, the environment, and climate. For example, in this report we did not analyze the reductions in barge shipments on the Mississippi River due to lower river levels, the increases in forest fires due to dry conditions, or the impacts of disappearing prairie potholes on ducks; all these impacts were made vivid during 1988. The drought reminded us of our vulnerability as a nation, but it cannot be viewed as a prediction of things to come.

MAJOR FINDINGS

The findings collectively suggest a world different from the world that exists today, although there are many uncertainties about specific effects. Global climate change could have significant implications for natural ecosystems; for where and how we farm; for the availability of water to irrigate crops, produce power, and support shipping; for how we live in our cities; for the wetlands that spawn our fish; for the beaches we use for recreation; and for all levels of government and industry.

The rate of global warming may be the most important factor affecting both natural and managed systems. The faster the warming, the harder it will be to adapt. The ability of natural ecosystems (forests, wetlands, barrier islands, national parks) to adapt to a rapidly warming climate is limited. Rates of natural migration and adaptation could be much slower than the rate of climate change. Populations of many species and inhabited ranges could decrease, and many may face extinction. The ultimate effects could last for centuries and would be virtually irreversible. Whether human intervention could mitigate these effects was not studied.

Managed systems may show more resilience. For example, although sea level rise may put additional stresses on coastal cities and although changes in temperature and rainfall patterns may require new strategies for managing water resources and agriculture, we could adapt to changing climate relatively quickly, if we have enough financial resources. We would expect that basic requirements for food and water could be met in the United States (as crops are shifted and water management systems are modified), and that developed areas with high economic value could be protected against sea level rise (as bulkheads and levees are built). The total cost of adapting to global climate change is beyond the scope of this report. It appears it could be expensive, but affordable, for a highly industrialized country like the United States to adapt managed systems in response to gradual global warming. If change comes more quickly, adaptation by managed systems will be more difficult and expensive. If it comes more slowly, the cost and difficulty of adaptation will be less.

In many cases, the results of our analysis appear to be consistent across scenarios, because either increasing temperatures or higher sea levels dominate the systems that were studied. For example, higher temperatures would cause earlier snowmelt, a northward migration of forests, and a northward shift in crops, and higher sea levels could inundate wetlands and low-lying areas. In other cases, however, only a range of values can be presented because uncertainties in an important variable, such as precipitation, make the direction of change highly uncertain.

The main findings and policy implications of this report are presented in national and regional chapters. They are summarized in the following pages, but the reader is urged to explore the full report to understand the complete context of these results.

NATIONAL FINDINGS

Natural Systems

The location and composition of various plants and animals in the natural environment depend, to a great extent, on climate. Trees grow in certain areas and fish exist in streams and lakes because the local climate and other conditions are conducive to reproduction and growth. A major focus of thus report was to identify what may happen to plants and animals, as a result of climate change -- whether they would survive in their current locations or be able to migrate to new habitats, and how soon these ecosystems could be affected. The following descriptions of impacts on natural systems are subject to uncertainties about climate change and the responses of natural systems to such change.

Natural Systems May Be Unable to Adapt Quickly to a Rapid Warming

If current trends continue, climate may change too quickly for many natural systems to adapt. In the past, plants and animals adapted to historic climate changes over many centuries. For example, since the last ice age 18,000 years ago, oak trees migrated northward from the southeastern United States as the ice sheet receded. Temperatures warmed about 5°C (9°F) over thousands of years, but they rose slowly enough for forests to migrate at the same rate as climate change. In the future, the greenhouse effect may lead to similar changes in the magnitude of warming, but the changes may take place within a century. Climate zones may shift hundreds of miles northward, and animals and especially plants may have difficulty migrating northward that quickly.

Forests

Forests occupy one-third of the land area of the United States. Temperature and precipitation ranges are among the determinants of forest distributions. Forests are also sensitive to soils, light intensity, air pollution, pests and pathogens, disturbances such as fires and wind, and management practices.

Several approaches were used to examine geographic shifts in forests. Potential ranges of forests were estimated for eastern North America using temperature and precipitation correlations from pollen data. Changes in composition and abundance of particular forests were estimated for particular sites in the Great Lakes and Southeast using site-specific models. These regions were chosen to represent a diversity of forest types and uses. Finally, the ability of trees to migrate to new habitats was analyzed using shifts in climate zones from GCMs and historic rates of tree migration. This study focused on several species that are widely dispersed across the northeastern United States. The direct effects of CO_2, which could change water-use efficiency, pest interactions, and the competitive balance among plants, were not modeled, nor were reforestation or the suitability of soils and sunlight considered. It is not clear how these results would have been affected if such factors had been included.

The Range of Trees May Be Reduced

Figure 4 shows the potential shifts in forest ranges in response to climate change. The scenarios assume that climate change could move the southern boundary northward by 600-700 km (approximately 400 miles), while the northern boundary would move only as

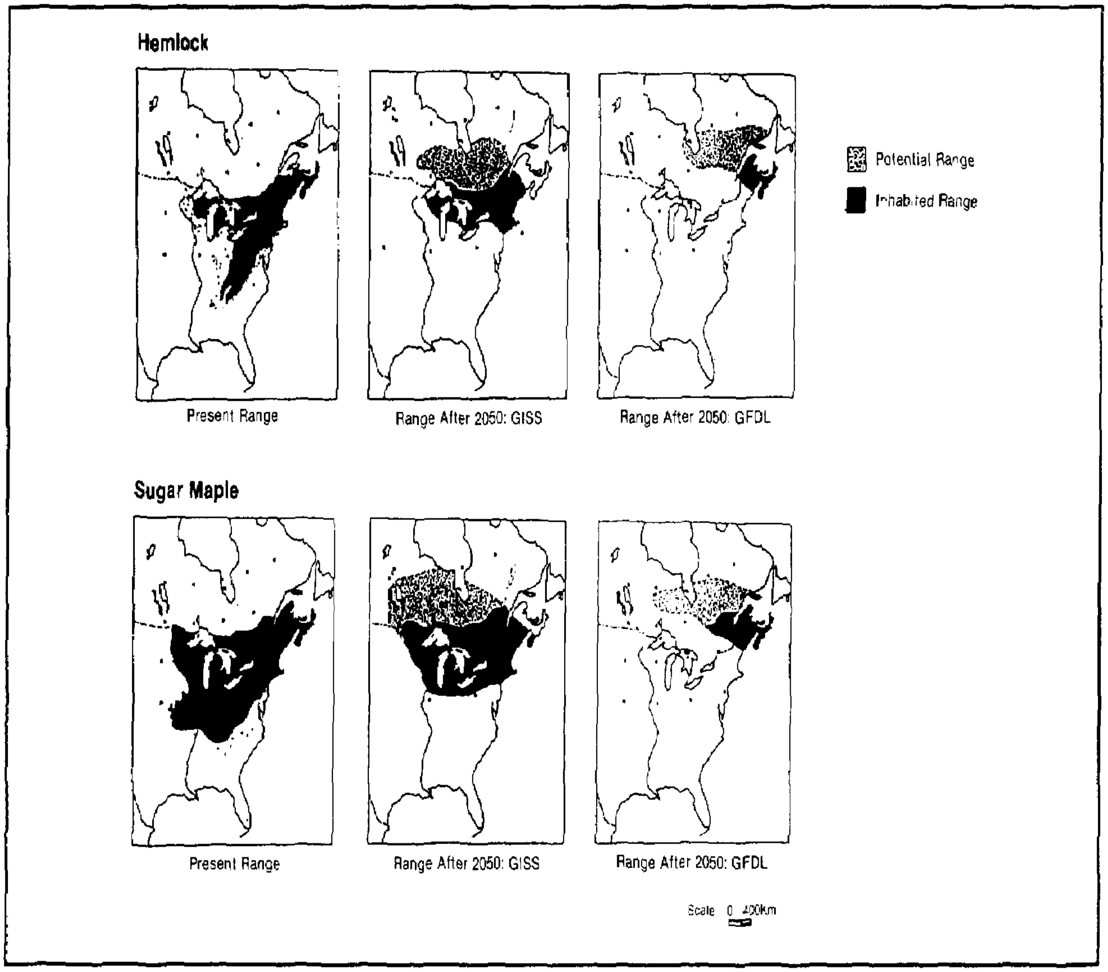


Figure 4. Shifts in range of hemlock and sugar maple under alternative climate scenarios.

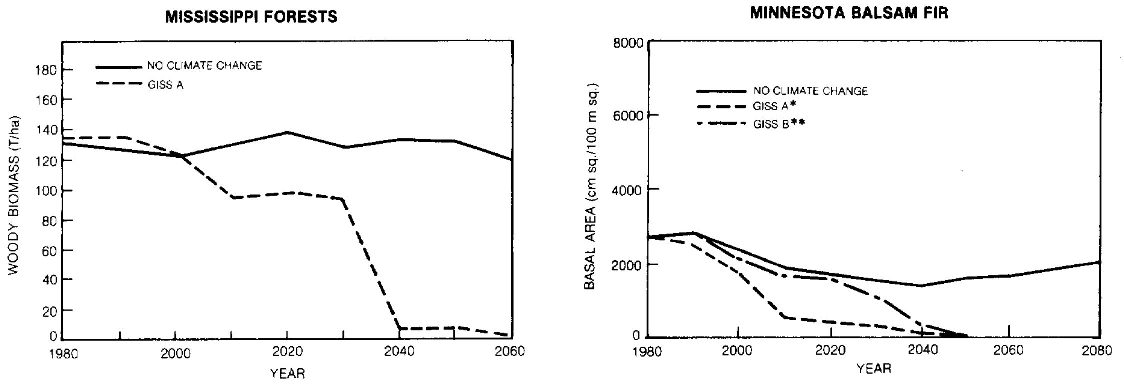
fast as the rate of migration of forests. Assuming a migration rate of 100 km (60 miles) per century, or double the known historic rate, the inhabited ranges of forests could be significantly reduced because the southern boundary may advance more quickly than the northern boundary. Even if climate stabilizes, it could take centuries for migration to reverse this effect. If climate continues to warm, migration would continue to lag behind shifts in climate zones. If elevated CO_2 concentrations increase the water use efficiency of tree species and pest infestations do not worsen, the declines of the southern ranges could be partly alleviated. Reforestation could help speed the migration of forests into new areas.

Changes in Forest Composition Are Likely

Climate change may significantly alter forest composition and reduce the land area of healthy forests. Higher temperatures may lead to drier soils in many parts of the country. Trees that need wetter soils may die, and their seedlings could have difficulty surviving these conditions. A study of forests in northern Mississippi and northern Georgia indicated that seedlings currently in such areas would not grow because of high temperatures and dry soil conditions. In central Michigan, forests now dominated by sugar maple and oak may be replaced by grasslands, with some sparse oak trees surviving. These analyses did not consider the introduction of species from areas south of these regions. In northern Minnesota, the mixed boreal and northern hardwood forests could become entirely northern hardwoods. Some areas might experience a decline in productivity, while others (currently saturated soils) might have an increase. The process of changes in species composition would most likely continue for centuries. Other studies of the potential effects of climate change in forests imply northward shifts in ranges and significant changes in composition, although specific results vary depending on sites and scenarios used.

Changes May Begin in 30 to 80 Years

Forest change may be visible in a few decades from now. This would involve a faster rate of mortality among mature trees and a decline in seedlings and growth of new species. The studies of forests in the Southeast and Great Lakes indicate that these forests could begin to die back in 30 to 80 years. Figure 5 displays possible reductions in balsam fir trees in northern Minnesota and forests in Mississippi in response to two different scenarios of warming. At the same time in Minnesota, for example, sugar maple could become more abundant. These forests appear to be very



*** Assumes constant exponential growth in emissions**

**** Assumes constant arithmetic growth in emissions**

Figure 5. Forest declines due to temperature increases.

sensitive to small changes in climate, because dieback starts to become noticeable after an approximate 1 to 1.5°C warming. Once this process starts, major dieback may occur rapidly. The timing of a decline is sensitive to the rate of climate change; a warming slower than that assumed in the scenarios would delay the dieback.

Other Factors Will Influence Forest Health

The health of forests will not be determined by climate change alone. The drier soils expected to accompany climate change could lead to more frequent fires, warmer climates may cause changes in forest pests and pathogens, and changes in air pollution levels could reduce the resilience of forests. Continued depletion of stratospheric ozone would also further stress forests. None of these outcomes was considered by the forest studies in this report, although they could speed forest declines.

Biodiversity

Biological diversity can be defined as the variety of species in ecosystems, and the genetic variability within each species and the variety of ecosystems around the world. Over 400 species of mammals, 460 species of reptiles, 660 species of freshwater fishes, and tens of thousands of invertebrate species can be found in this country, in addition to some 22,000 plant species. About 650 species of birds reside in or pass through the United States annually. Biological diversity is needed to provide food, medicine, shelter, and other important products.

This report examined the impacts of climate change on specific plants and animals by using climate change scenarios and models of particular species or systems within a region. Analyses have been performed for impacts on finfish and shellfish in the Apalachicola Bay in the Florida Panhandle, fish in the Great Lakes, and marine species in San Francisco Bay. Additional information on potential impacts on biodiversity was gathered from the published literature.

Extinction of Species Could Increase

Historic climate changes, such as the ice ages, have led to extinction of many species. More recently, human activities, such as deforestation, have greatly accelerated the rate of species extinction. The faster rate of climate warming due to the greenhouse effect, absent an active program to preserve species, would most likely lead to an even greater loss of species. The uncertainties surrounding the rate of warming, the response of individual species, and interspecies dynamics make it difficult to assess the probable impacts, although natural ecosystems are likely to be destabilized in unpredictable ways.

As with trees, other plants and animals may have difficulty migrating at the same rate as a rapidly changing climate, and many species may become extinct or their populations maybe reduced. The presence of urban areas, agricultural lands, and roads would restrict habitats and block many migratory pathways. These obstacles may make it harder for plants and wildlife to survive future climate changes. On the other hand, some species may benefit from climate change as a result of increases in habitat size or reduction in population of competitors. The extent to which society can mitigate negative impacts through such efforts as habitat restoration is not clear.

Impacts on Fisheries Would Vary

Freshwater fish populations may grow in some areas and decline in others. Fish in such large water bodies as the Great Lakes may grow faster and may be able to migrate to new habitats. Increased amounts of plankton could provide more forage for fish. However, higher temperatures may lead to more aquatic growth, such as algal blooms, and decreased mixing of lakes (longer stratification), which would deplete oxygen levels in shallow areas of the Great Lakes, for example Lake Erie, and make them less habitable for fish. Fish in small lakes and streams may be unable to escape temperatures beyond their tolerances, or their habitats may simply disappear.

Warmer temperatures could also exceed the thermal tolerance of many marine finfish and shellfish in some southern locations, although some marine species could benefit. The full impacts on marine species are not known at this time. The loss of coastal wetlands could further reduce fish populations, especially shellfish. And while increased salinity in estuaries could reduce the abundance of freshwater species, it could increase the presence of marine species. Whether finfish and shellfish could migrate to new areas and the effectiveness of restocking were not studied.

Effects on Migratory Birds Would Depend on Impacts on Habitats

Migratory birds are likely to experience mixed effects from climate change, with some arctic nesting herbivores benefiting, and continental nesters and shorebirds suffering. Some winter habitats could experience increased productivity. On the other hand, the loss of wintering grounds, which may result from sea level rise and changing climate, could harm many species, as would the loss of inland prairie potholes resulting from potentially increased midcontinental dryness.

Sea Level Rise

A rise in sea level is one of the more probable impacts of climate change. Higher global temperatures will expand ocean water and melt some mountain glaciers, and may eventually cause polar ice sheets to discharge ice. Over the last century, global sea level has risen 10 to 15 cm (4 to 6 inches), and along the U.S. coastline, relative sea level rise (which includes land subsidence) has averaged about 30 cm (1 foot). Published estimates of sea level rise due to global warming generally range from 0.5 to 2.0 meters (1.5 to 7 feet) by 2100. Sea level rise could be greater than or less than this range because uncertainties exist regarding the rate of atmospheric warming, glacial processes, oceanic uptake of heat, precipitation in polar areas, and other variables.

The studies estimate the potential nationwide loss of wetlands, and the cost of defending currently developed areas from a rising sea, for three scenarios (50, 100, and 200 cm) of sea level rise by the year 2100. The scenarios are based on quantitative estimates of sea level rise, but no probabilities have been attributed to them. Wetland loss estimates were based on remote-sensing data and topographic maps for a sample of sites along the U.S. coast. The cost of holding back the sea was based on (1) the quantity of sand necessary to elevate beaches and coastal barrier islands as sea level rises; (2) rebuilding roads and elevating structures; and (3) constructing levees and bulkheads to protect developed lowlands along sheltered waters.

Protecting Developed Areas May Be Expensive

Given the high property values of developed coastlines in the United States, it is likely that measures would be taken to hold back the sea along most developed shores. Preliminary estimates suggest that the cumulative capital cost (including response to current sea level rise) of protecting currently developed areas would be $73 to $111 billion (in 1988 dollars) through 2100 for a 1-meter global rise (compared with $4 to $6 billion to protect developed areas from current trends in sea level rise). A 1-meter sea level rise would lead to a cumulative inundation of 7,000 square miles of dryland -- an area the size of Massachusetts (see Table 1). If the oceans continue to rise at current rates, approximately 3,000 square miles of dryland would be lost.

Most Coastal Wetlands Would Be Lost

Historically, wetlands have kept pace with a slow rate of sea level rise. However, in the future, sea level will probably rise too fast for some marshes and swamps to keep pace. Although some wetlands can survive by migrating inland, a study on coastal wetlands estimated that for a 1-meter rise, 26 to 66% of wetlands would be lost, even if wetland migration were not blocked. A majority of these losses would be in the South (see Table 2). Efforts to protect coastal development would increase wetland losses, because bulkheads and levees would prevent new wetlands from forming inland. If all shorelines are protected, 50 to 82% of wetlands would be lost. The different amounts of dryland lost for different regions and scenarios are shown in Figure 6.

The loss of wetland area would have adverse ecological impacts, with the ability of ecosystems to survive a rising sea level depending greatly on how shorelines are managed. For many fish and shellfish species, the fraction of shorelines along which wetlands can be found is more important than the total area of wetlands. This fraction could remain at approximately present levels if people do not erect additional bulkheads and levees. In Louisiana, with 40% of U.S. coastal wetlands, large areas of wetlands are already being converted to open water as a result of natural subsidence and the effects of human activities, and most could be lost by 2030 if current trends continue.

Estuaries May Enlarge and Become More Saline

Although future riverflows into estuaries are uncertain, a rise in sea level would increase the size and salinity of estuaries and would increase the salinity of coastal aquifers. For example, sea level rise may result in a more saline and enlarged Sacramento-San Joaquin Delta, and Miami, New York, and other coastal communities would have to set up current efforts to combat salinity increases in surface water of the gross national product in 1985, with farm assets totaling $771 billion. Crop production is sensitive to climate, soils, management methods, and many other factors. During the Dust Bowl years of the 1930s, wheat and corn yields dropped by up to 50%, and during the drought of 1988,

Table 1. Nationwide Impacts of Sea Level Rise

		Sea Level Rise by 2100		
Alternative	Baseline	50 cm	100 cm	200 cm
If Densely Developed Areas Are Protected				
Shore protection costs (billions of 1986 dollars)	4-6	32-43	73-111	169-309
Dryland lost (mi^2)	1,500-4,700	2,200-6,100	4,100-9,200	6,400-15,400
Wetlands lost (%)	9-25	20-45	29-69	33-80
If No Shores Are Protected				
Dryland lost (mi^2)	N.C.	3,300-7,300	5,100-10,300	8,200-15,400
Wetlands lost (mi^2)	N.C.	17-43	26-66	29-76
If All Shores Are Protected				
Wetlands lost (%)	N.C.	38-61	50-82	66-90

N.C. = Not calculated.
*Baseline assumes current global sea level rise trend of 12 cm per century. Given costal subsidence trends, this implies about a 1-foot rise in relative sea level along most of the U.S. coast.
Source: Assembled by Titus and Greene.

Table 2. Loss of Coastal Wetlands from a One-Meter Rise in Sea Level

Region	Current wetlands area (mi2)	All dryland protected (% loss)	Current development protected loss (%)	No protection (% loss)
Northeast	600	16	10	2
Mid-Atlantic	746	70	46	38
South Atlantic	3,813	64	44	39
South and West Florida	1,869	44	8	7
Louisiana[a]	4,835	77	77	77
Other Gulf	1,218	85	76	75
West	64	56	gain[b]	gain[b]
United States	13,145	50-82	29-69	26-66

a Louisiana projections do not consider potential benefits of restoring flow of sediment and freshwater.
b Potential gain in wetland acreage not shown because principal author suggested that no confidence could be attributed to those estimates. West Coast sites constituted less than 0.5% of wetlands in study sample.
Source: Adapted from Park et al.

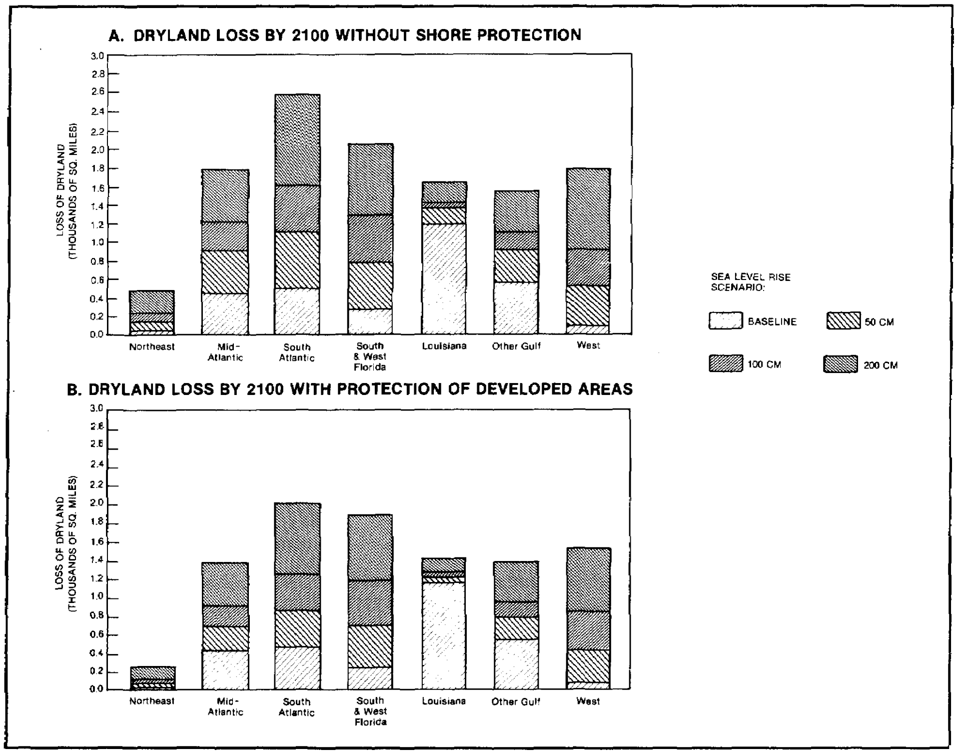


Figure 6. Dryland loss by 2100.

corn yields declined about 40%.

The agricultural analyses in this report examined potential impacts on crop yields and productivity from changes in climate and direct effects of CO_2. (Higher CO_2 concentrations may increase plant growth and water-use efficiency.) The studies used high estimates of the beneficial effects of CO_2 on crops. Changes in dryland and irrigated corn, wheat, and soybean yields and in irrigation demand were estimated for the Southeast, Great Plains, and Great Lakes regions using widely validated crop growth models. Crop yield changes

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Agriculture

The temperate climate and rich soils in the United States, especially in the Midwest, have helped make this country the world's leading agricultural producer. Agriculture, a critical component of the U.S. economy, contributed 17.5% of the gross national product in 1985, with farm assets totaling $771 billion. Crop production is sensitive to climate, soils, management methods, and many other factors. During the Dust Bowl years of the 1930s, wheat and corn yields dropped by up to 50%, and during the drought of 1988, corn yields declined about 40%.

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The estimated yield changes from the four regional crop modeling studies and runoff changes from the GCMs were used in a nationwide agricultural economic model to estimate regional and national changes in crop production, land use, and demand for irrigation. The economic model did not consider the introduction of new crops, changes in government policies on agriculture, change in demand for water for nonagricultural uses, and global agricultural changes. Both a modeling study and a literature review were used to estimate changes in plant-pest interactions. An agricultural runoff and leaching model was used to estimate potential changes in water quality in the Great Plains. Some farm-level adjustments, including the effects of changed planting dates and use of different varieties, were investigated in various studies, and the potential national implications on livestock were analyzed using modeling studies and a literature review.

Yields Could Be Reduced, Although the Combined Effects of Climate and CO_2 Would Depend on the Severity of Climate Change

In most regions of the country, climate change alone could reduce dryland yields of corn, wheat, and soybeans, with site-to-site losses ranging from negligible amounts to 80%. These decreases would be primarily the result of higher temperatures, which would shorten a crop's life cycle. In very northern areas, such as Minnesota, dryland yields of corn and soybeans could increase as warmer temperatures extend the frost-free growing season. The combined effects of climate change and increased CO_2 may result in net increases in yields in some cases, especially in northern areas or in areas where rainfall is abundant. In southern areas, however, where heat stress is already a problem, and in areas where rainfall is reduced, crop yields could decline.

Productivity May Shift Northward

Under all of the scenarios (with and without the direct effects of increased CO_2), the relative productivity of northern areas for the crops studied was estimated to rise in comparison with that of southern areas. In response to the shift in relative yields, grain crop acreage in Appalachia, the Southeast, and the southern Great Plains could decrease, and acreage in the northern Great Lakes States, the northern Great Plains, and the Pacific Northwest could increase (see Figure 7). A change in agriculture would affect not only the livelihood of farmers but also agricultural infrastructure and other support services. The sustainability of crop production in northern areas was not studied. Changes in foreign demand for U.S. crops, which would likely be altered as a result of global warming and could significantly alter the magnitude of the results, were not considered in this analysis.

The National Supply of Agricultural Commodities May Be Sufficient to Meet Domestic Needs, But Exports May Be Reduced

Even under the more extreme climate change scenarios, the production capacity of U.S. agriculture was estimated to be adequate to meet domestic needs. Only small to moderate economic losses were estimated when climate change scenarios were modeled without the beneficial effects of CO_2 on crop yields. When the combined effects of climate and CO_2 were considered, results were positive with a relatively wetter climate change scenario and negative with the hotter, drier climate change scenario. Thus, the severity of the economic consequences could depend on the type of climate change that occurs and the ability of the direct effects of CO_2 to enhance yields. A decline in crop production would reduce exports, which could have serious implications for food-importing nations. If climate change is severe, continued and substantial improvements in crop yields would be needed to fully offset the negative effects. Technological improvements, such as improved crop varieties from bioengineering, could be helpful in keeping up with climate change. These results could be affected by global changes in agriculture, which were not considered in the analysis.

Farmers Would Likely Change Many of Their Practices

Farm practices would likely change in response to different climate conditions. Most significantly, in many regions, the demand for irrigation is likely to increase as a result of higher temperatures. If national productivity declines, crop prices may rise, making irrigation more economical and increasing the use of it (see Figure 8). Irrigation equipment may be installed in

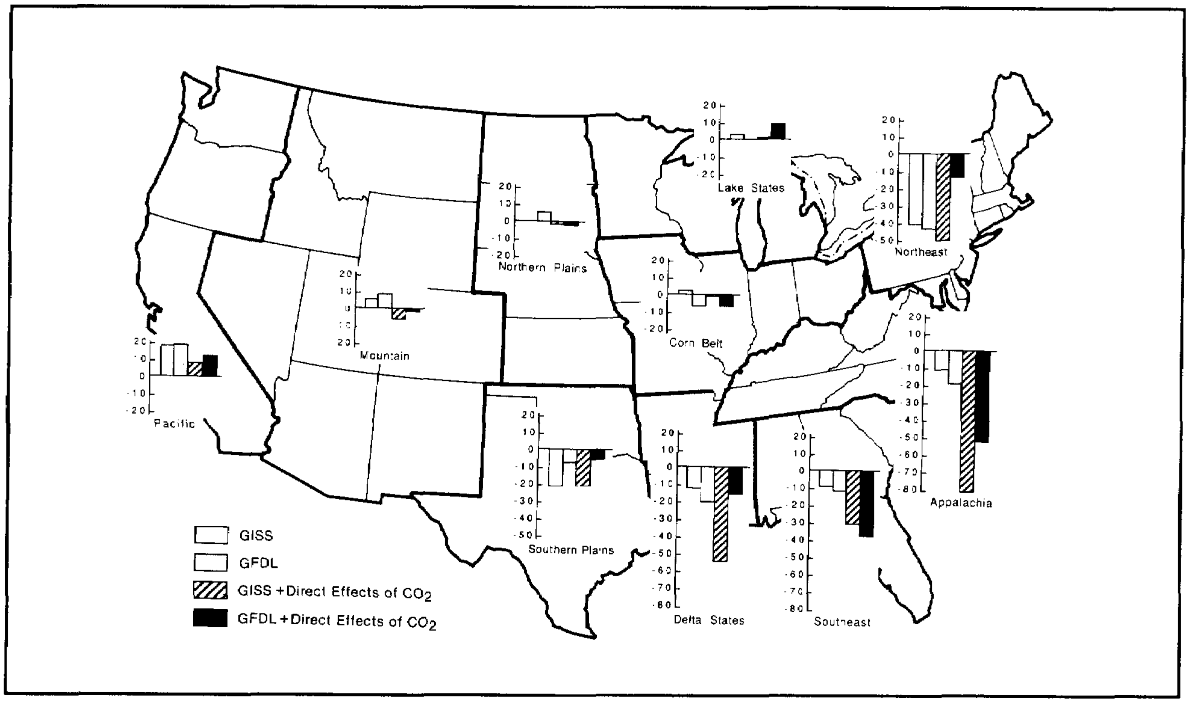


Figure 7. Percent change in regional agricultural acreage.

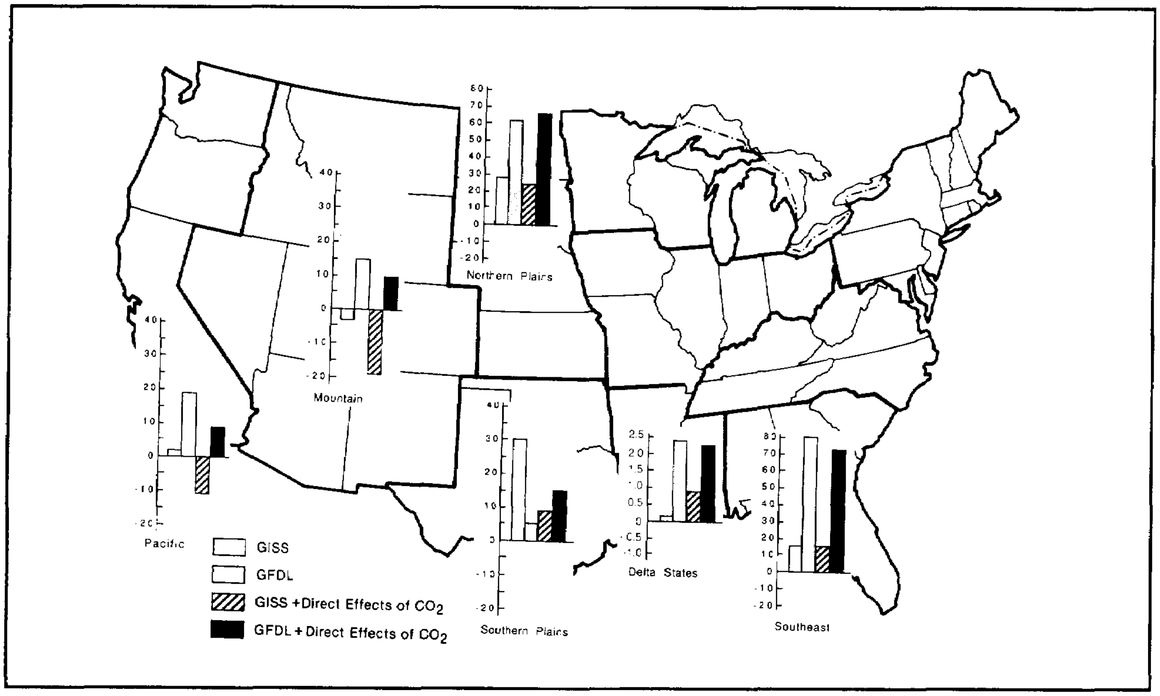


Figure 8. Change in regional irrigation acreage (100,000 of acres).

many areas that are currently dryland farms, and farmers already irrigating may extract more water from surface and groundwater sources. Changes in competing demands for water by municipal and industrial users, which could raise the cost of irrigation, were not considered. Farmers may also switch to more heat- and drought-resistant crop varieties, plant two crops during a growing season, and plant and harvest earlier. Whether these adjustments would compensate for climate change depends on a number of factors, including the severity of the climate change. Under extreme climate change conditions, some farms could be abandoned.

Ranges of Agricultural Pests May Extend Northward

Warmer temperatures may result in the northward extension of the range of diseases and pests that now afflict livestock in the South, and could make conditions more favorable for the introduction of new livestock diseases into the southern United States. This extension could reduce crop yields and affect livestock.

Shifts in Agriculture May Harm the Environment in Some Areas

Expansion of irrigation and shifts in regional production patterns imply more competition for water resources, greater potential for surface water and groundwater pollution, loss of some wildlife habitats, and increased soil erosion. A northward migration of agriculture would increase the use of irrigation and fertilizers on sandy soils, thus endangering the quality of underlying groundwater. Chemical pesticide usage may change to control different crop and livestock pests. Thus, climate change could exacerbate environmental pollution and increase resource use from agriculture in some areas.

Water Resources

The United States is endowed with a bountiful supply of water, but the water is not always in the right place at the right time or of the right quality. In some regions, such as the Great Basin and the Colorado River Basin, the gap between demand and supply of water is narrow. In these basins, such offstream uses as irrigation and domestic consumption often conflict with each other and with other needs, such as maintaining flow to preserve environmental quality.

Although global precipitation is likely to increase, it is not known how regional rainfall patterns will be affected. Some regions may have more rainfall, while others may have less. Furthermore, higher temperatures would most likely increase evaporation. These changes would likely create new stresses for many water management systems.

To discuss the potential impacts of climate change on water resources, this report studied water resources in California, the Great Lakes, and the Southeast, estimated the demand for irrigation in the Great Plains, and drew on information from the literature. These studies focused on changes in runoff and, for California and the Southeast, considered management responses. The studies examined the water management systems as they are currently configured and did not examine new construction. Among other factors not considered were changes in demand for water resources (which would most likely lead to greater changes in water management systems) and changes in vegetation due to climate change and increased CO_2, which could affect runoff. The studies did not estimate impacts on groundwater.

The Direction of Change in Some Water Bodies Can Be Estimated, but Total Impacts in the United States Cannot Be Determined

Results of hydrology studies indicate that it is possible in some regions to identify the direction of change in water supplies and quality due to global warming. For example, in California, higher temperatures would reduce the snowpack and cause earlier melting. Earlier runoff from mountains could increase winter flooding and reduce deliveries to users. In the Great Lakes, reduced snowpack combined with potentially higher evaporation could lower lake levels (although certain combinations of conditions could lead to higher levels). In other areas, such as the South, little snowcover currently exists, so riverflow and lake levels depend more on rainfall patterns. Without better rainfall estimates, we cannot determine whether riverflow and lake levels in the South would rise or fall.

Water Quality in Many Basins Could Change

Changes in water supply could significantly affect water quality. Where riverflow and lake levels decline, such as in the Great Lakes, there would be less water to dilute pollutants. On the other hand, where there is more water, water quality may improve. Higher temperatures may enhance thermal stratification in some lakes and increase algal production, degrading water quality. Changes in runoff and leaching from farms and potential increases in the use of irrigation for agriculture could affect surface and groundwater quality in many areas.

Water Use Conflicts May Increase

In some regions, decreased water availability and increased demand for water, such as for irrigation and powerplant cooling, may intensify conflicts among offstream uses. Conflicts between these offstream uses and instream uses such as flood control and wildlife habitat also may be intensified.

Electricity Demand

The demand for electricity is influenced by economic growth, by changes in industrial and residential/commercial technologies, and by climate. The principal climate-sensitive electricity end uses are space heating and cooling and, to a lesser degree, water heating and refrigeration. These uses of electricity may account for up to a third of total sales for some utilities and may contribute an even larger portion of seasonal and daily peak demands.

This report analyzed potential changes in the national demand for electricity in 2010 and 2055, using the relationship between demand and climate for several major utility systems. The study estimated changes in demand due to nonclimate factors, such as increases in population and GNP. The impacts of climate change are expressed as an increase over non-climate growth, and results are given on nationwide and regional bases. The study did not consider changes in technology and improvements in energy efficiency; the impacts of higher temperatures on the demand for natural gas and oil for home heating, which will most likely decrease; changes in electricity supplies, such as hydropower; or changes in demand for electricity for such uses as irrigation.

National Electricity Demand Would Rise

Global warming would increase annual demand for electricity and total generating capacity requirements in the United States. The demand for electricity for summer cooling would increase, and the demand for electricity for winter heating would decrease. Annual electricity generation in 2055 was estimated under the transient scenarios to be 4 to 6% greater than without climate change. The annual costs of meeting the increase due to global warming, assuming no change in technology or efficiency, was estimated to be $33-$73 billion (in 1986 dollars). These results differ on a regional basis and are shown in Figure 9. States along the northern tier of the United States could have net reductions in annual demand of up to 5%, because decreased heating demand would exceed increased demand for air-conditioning. In the South, where heating needs are already low, net demand was estimated to rise by 7 to 11% by 2055.

Generating capacity requirements are determined largely by peak demand, which occurs in the summer in all but the far northern areas of the country. By 2010, generating requirements to meet increased demand could rise by 25 to 55 gigawatts (GW), or by 9 to 19% above new capacity requirements, assuming no climate change. By 2055, generating requirements could be up by 200 to 400 GW, or 14 to 23% above non-climate-related growth. The cumulative cost of such an increase in capacity, assuming no change in technology or improvements in energy efficiency, was estimated to be between $175 and $325 billion (in 1988 dollars). The South would have a greater need than the North for additional capacity, as shown in Figure 10. Increases in capacity requirements could range from 0 to 10% in the North, to 20 to 30% in the South and Southwest. U.S. emissions of such greenhouse gases as CO_2 could increase substantially if additional powerplants are built to meet these capacity requirements, especially if they burn coal. Improvement in the efficiency of energy production and use would reduce these emissions.

Air Quality

Air pollution caused by emissions from industrial and transportation sources is a subject of concern in the United States. Over the last two decades, considerable progress has been made in improving air quality by reducing emissions. Yet high temperatures in the summer of 1988 helped raise tropospheric ozone levels to all-time highs in many U.S. cities. But air quality is also directly affected by other weather variables, such as windspeed and direction, precipitation patterns, cloud cover, atmospheric water vapor, and global circulation patterns.

A literature review of the relationship between climate and air pollution was conducted for this report. In addition, air quality models were used for a preliminary analysis of the changes in ozone levels in

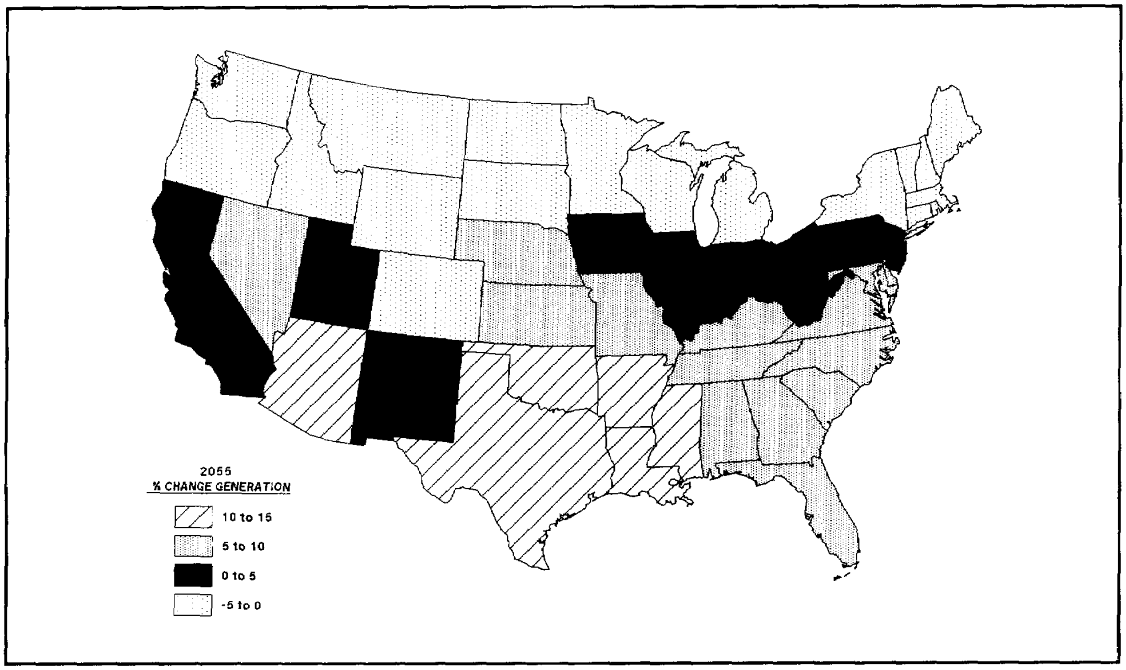


Figure 9. Changes in electricity generation by state, induced by climate change scenarios by 2055.

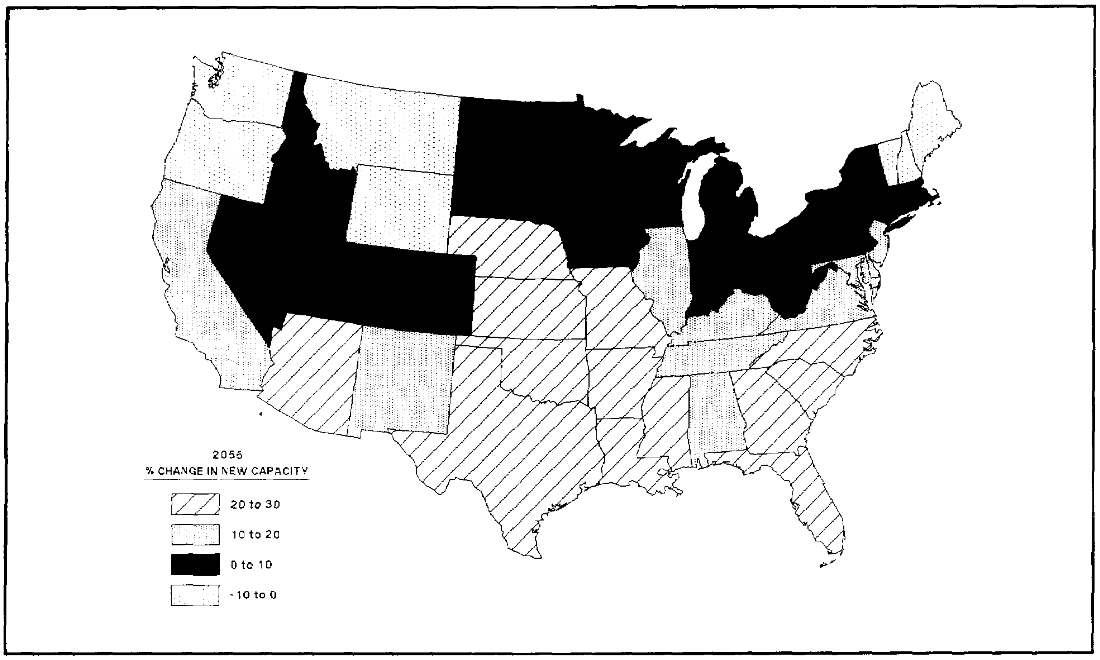


Figure 10. Changes in electricity capacity by state, induced by climate change scenarios in 2055.

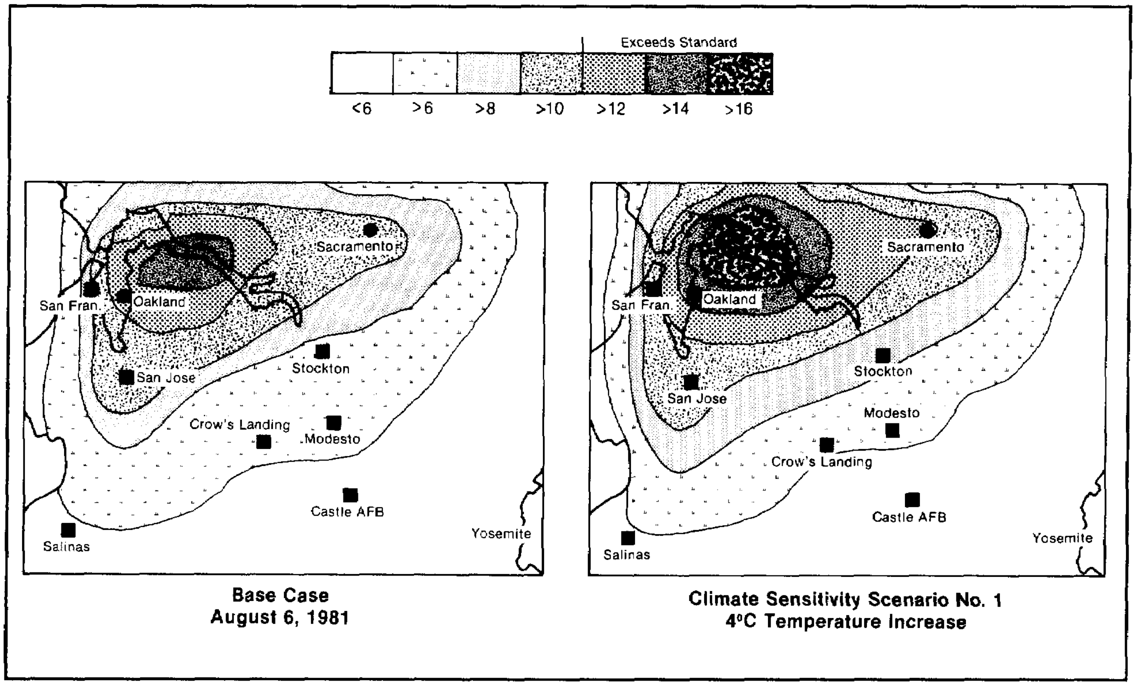
several regions. The latter analysis did not consider reduction in emissions of air pollutants due to enforcement of the Clean Air Act.

<u>Climate Changes Could Increase Air Pollution, Especially Smog</u>

A rise in global temperatures would increase manmade and natural emissions of hydrocarbons and manmade emissions of sulfur and nitrogen oxides over what they would be without climate change. Natural emissions of sulfur would also change, but the direction is uncertain. Although the potential magnitude of the impacts of the increased emissions on air quality is uncertain, higher temperatures would speed the reaction rates among chemicals in the atmosphere, causing higher ozone pollution in many urban areas than would occur otherwise. They would also increase the length of the summer season, usually a time of high air pollution levels. As shown in Figure 11, preliminary analyses of a 4°C temperature increase in the San Francisco Bay area (with no changes in other meteorologic variables, such as mixing heights), assuming no change in emissions from current levels, suggest that maximum ozone concentrations would increase by 20%, and that the area exceeding the National Ambient Air Quality Standards would almost double. Studies of the Southeast also show expansion of the areas violating the standards, but they show smaller changes in levels. Although the impacts of higher temperatures on acid rain were not analyzed, it is likely that sulfur and nitrogen would oxidize more rapidly under higher temperatures. The ultimate effect on acid deposition is difficult to assess because changes in clouds, winds, and precipitation patterns are uncertain.

Health Effects

Human illness and mortality are linked in many ways to weather patterns. Weather affects contagious diseases such as influenza and pneumonia, and allergic diseases such as asthma. Mortality rates, particularly for the elderly and the very ill, are influenced by the frequency and severity of extreme temperatures. The life cycles of disease carrying insects, such as mosquitoes and ticks, are affected by changes in temperature and rainfall, as well as by habitat, which is itself sensitive to climate. Finally, increased air pollution, which is related to weather patterns, can heighten the incidence and severity of such respiratory diseases as emphysema and asthma.



Base Case
August 6, 1981

Climate Sensitivity Scenario No. 1
4°C Temperature Increase

Figure 11. Changes in the maximum daily ozone concentrations.

Both expert judgment and modeling were used to study the potential impacts of climate change on human health. A literature review and workshop were conducted to identify potential changes in vector-borne diseases caused by ticks, fleas, and mosquitoes (such as dengue and malaria). Models were used to estimate potential geographic shifts in the prevalence of Rocky Mountain spotted fever and malaria. Potential changes in mortality from heat and cold stress were quantitatively estimated, although such estimates did not consider changes in air pollution levels. The total impacts of climate change on human health are difficult to assess; these analyses looked at a limited number of potential effects and are only indicative of possible changes in mortality and morbidity.

Summer Mortality Could Increase, While Winter Mortality Could Decrease

Global warming may lead to changes in morbidity and increases in mortality, particularly for the elderly during the summer. Morbidity and mortality may decrease because of milder winters, although net mortality may increase. If the frequency or intensity of climate extremes increases, mortality is likely to rise. If people acclimatize by using air-conditioning, changing their workplace habits, and altering the construction of their homes and cities, the impact on summer mortality rates may be substantially reduced.

Regional Morbidity Patterns Could Change

Changes in climate as well as in habitat may alter the regional prevalence of vector-borne diseases. For example, some forests may become grasslands, thereby modifying the incidence of vector-borne diseases. Changes in summer rainfall could alter the amount of ragweed growing on cultivated land, and changes in humidity may affect the incidence and severity of skin infections and infestations such as ringworm, candidiasis, and scabies. Increases in the persistence and level of air pollution episodes associated with climate change would have other harmful health effects.

Urban Infrastructure

The value of municipal infrastructure in the United States, excluding buildings and electric power production, probably approaches one trillion dollars. The majority of the nation's investments are in water supply, wastewater transport and treatment facilities, drainage, roadways, airports, and mass transit facilities. Like the regions studied for this report, urban areas would feel a variety of impacts from climate change. This report examined the potential impacts of climate change on Cleveland, New York City, and Miami. These areas encompass a diversity of climates and uses of natural resources.

Much of the current inventory in urban infrastructure will most likely turn over in the next 35 to 50 years. A warmer global climate would require changes in the capital investment patterns of cities for water supplies, peak electric generating capacity, and storm sewer capacity. Urbanized coastal areas might have to invest additional billions of dollars into coastal protection to defend developed areas from a rising sea In Miami, for example, this could imply an increase of 1 to 2% in the city's capital spending over the next 100 years. Generally, northern cities such as Cleveland may fare better, since reductions in the operating and maintenance costs associated with heating public buildings, snow removal, and road maintenance should offset increasing costs for air-conditioning and port dredging (see Table 3).

REGIONAL IMPACTS

Studying the national impacts of climate change may disguise important differences in regional effects across the country. Shifting demands for economic and natural resources may cause stresses that cannot be seen at a national level. Furthermore, changes in one system, such as water supply, may affect other systems such as irrigation for agriculture. These combined effects may be most evident on a regional scale. The designs of the regional studies on agriculture, forests, and electricity were described above.

The studies discussed below considered only some of the potential regional impacts. Many potential impacts were not analyzed -- for example, demographic shifts into or out of the Southeast, recreational impacts in the Great Lakes, direct effects on such aquifers as the Ogallala in the Great Plains, and impacts on many specialty crops in California. In addition, current GCMs often disagree significantly about simulated regional changes, particularly about such key variables as precipitation. Their spatial resolution is roughly of the same size as the regions of concern; for example, there are two simulation points in California. The discussion that follows should not be viewed as

Table 3. Estimated Impacts of Doubled CO_2 Scenarios on Cleveland's Annual Infrastructure Costs (millions of 1987 dollars)

Cost category	Annual operating costs
Heating	-2.3
Air-conditioning	-2.7
Snow and ice control	-4.5
Frost damage to the roads	-0.7
Road maintenance	-0.5
Road reconstruction	-0.2
Mass transit	summer increase offsets winter savings
River dredging	less than $0.5
Water supply	negligible
Stormwater system	negligible
Total	-1.6 to +1.1

Source: Walker et al.

comprehensive, but rather as providing examples of important issues for each region.

California

California contains a highly managed water resource system and one of the most productive agricultural regions in the world. The state produces 14% of the nation's cash receipts for agriculture. California's water resources are poorly distributed in relation to its needs. Precipitation is abundant in the north, with the highest levels in the winter, while water is needed in the south for agriculture and domestic consumption. The Central Valley Project (CVP) and State Water Project (SWP) were built basically to capture runoff from the north and deliver it to uses in the south. These projects also provide flood protection, hydroelectric power, and freshwater flows to repel salinity (known as carriage water) in the Sacramento-San Joaquin River Delta. Islands in the delta are highly productive farmlands and are protected by levees.

The California case study focused on the Central Valley. First, changes in runoff in the valley were estimated. These results were then used to estimate changes in deliveries from the CVP and SWP and in agricultural water use. These results were combined with sea level rise estimates and were used to model how the salinity and shape of the San Francisco Bay estuary may change and how the demand for carriage water may be affected. The estimated changes in salinity and sea level rise were used to examine impacts on the ecology of the bay. Yield changes for a number of crops grown in the state were estimated, as were changes in ozone levels in central California and changes in electricity demand (see Figure 12).

California's Water Management System Would Have to Be Modified

Warmer temperatures would change the seasonality of runoff from the mountains surrounding the Central Valley. Runoff would be higher in the winter months as a result of less snowpack and more precipitation in the form of rain. Consequently, runoff would be lower in the late spring and summer. Under these conditions, the current reservoir system in the Central Valley would not have the capacity to provide adequate flood protection in the winter and store enough water to meet deliveries in the summer. Thus, much of the earlier winter runoff would have to be released. This would leave less water in the system for late spring and summer deliveries, when runoff would be lower. Under the three GCM scenarios, annual water deliveries from the SWP were estimated to decrease by 200,000 to 400,000 acrefeet (7 to 16% of supply). In contrast, the increase in statewide demand for water from the SWP due to non-climate factors, such as population growth, may total 1.4 million acre-feet by 2010. Reduced snowpack and earlier runoff could occur throughout the West, exacerbating water management problems in a region that is currently short of water.

Climate Change Is Likely to Increase Water Demand

On the whole, California's water demand could increase with a warmer climate. Twice as much carriage water may be needed to repel higher salinity levels resulting from a 1-meter sea level rise. In addition, consumptive uses may also increase. Irrigation, which may come from groundwater, may increase in some parts of the state. If new powerplants are built, they will need water for cooling, which could come from surface water supplies, depending on the location. Although it was not studied, municipal demand for water may also rise.

Sea Level Rise Would Affect the Size and Environment of San Francisco Bay

A sea level rise would increase the salt concentrations of San Francisco Bay. It is estimated that a 1-meter rise could cause the salt front in the Sacramento-San Joaquin River Delta to migrate upstream 4 to 10 km (2.5 to 6 miles). Sea level rise would also increase the difficulty of maintaining the Sacramento-San Joaquin Delta islands. If the levees around the delta islands were strengthened and raised, a 1-meter rise could increase the volume of the San Francisco Bay estuary by 15% and the area by 30%. If the levees were not maintained and the islands were flooded, there would be a doubling and tripling, respectively, of the volume and area of the bay. As a result of these changes, some wetlands would be lost, marine aquatic species would become relatively more abundant, and freshwater species would decline.

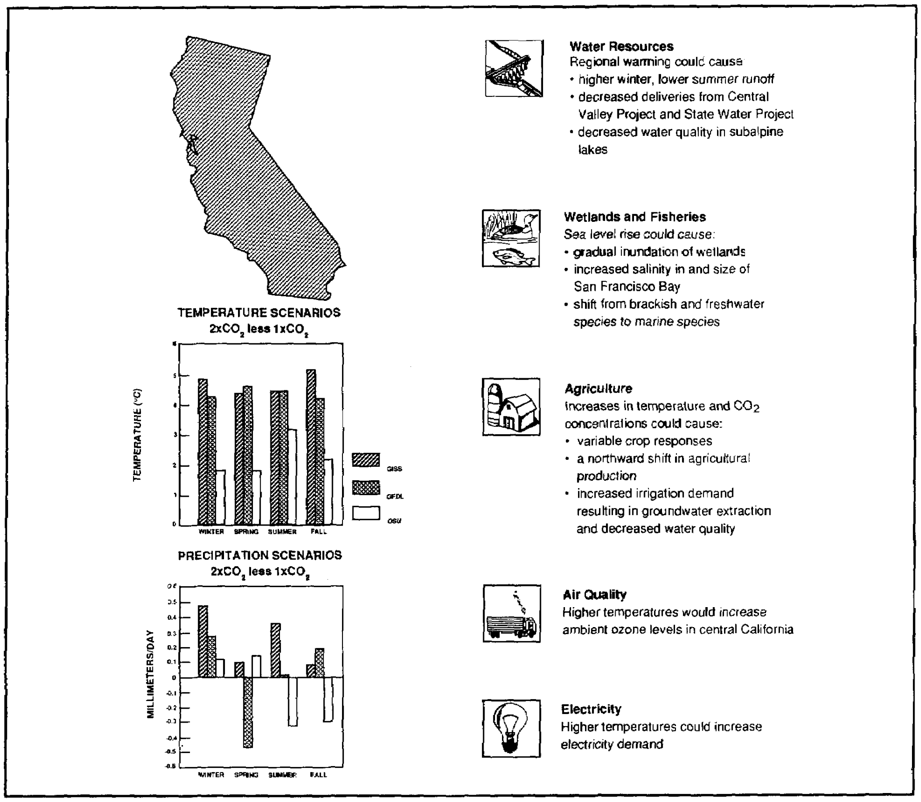


Figure 12. California

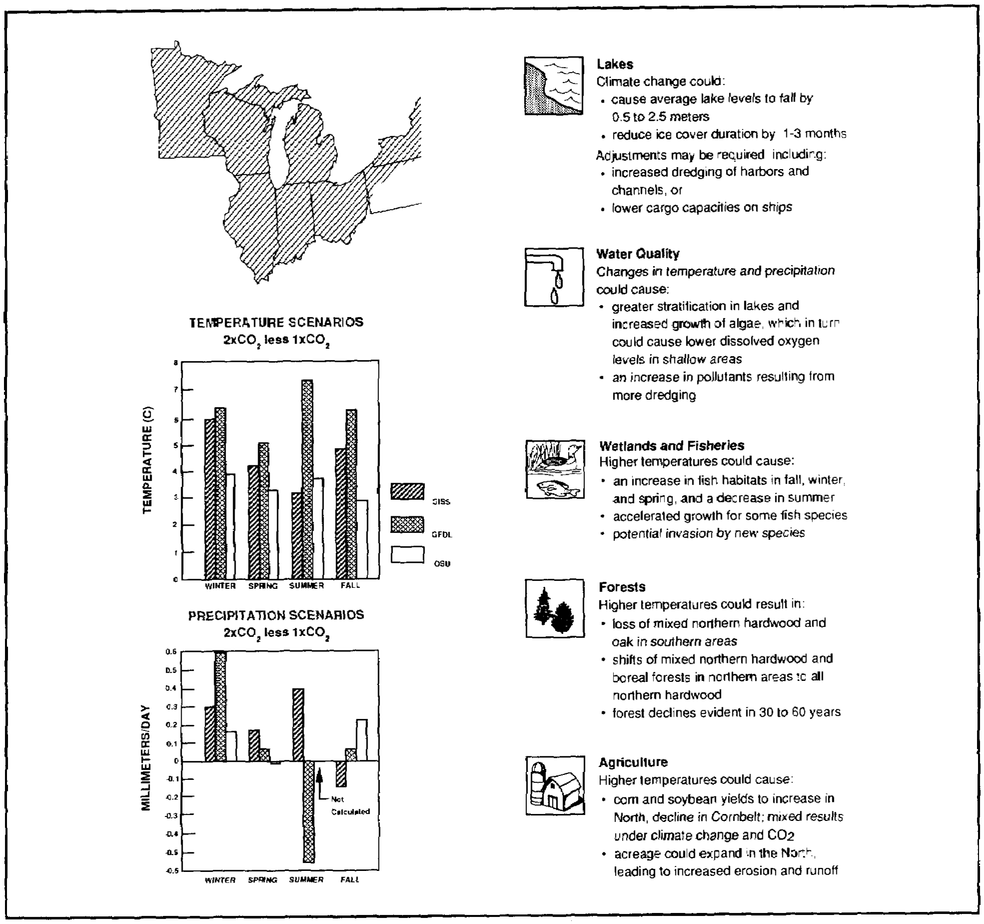
Climate Change Could Degrade Air Quality in California

Air quality is currently a major concern in California. The area of central California in violation of ozone quality standards could increase as a result of higher temperatures. Under one climate scenario, with a 4°C rise and current emission levels, the maximum size of the area with ozone levels in excess of the EPA standard of 0.12 ppm could double. This scenario assumed that such climate variables as windspeed and mixing height (the volume of air in which pollutants are diluted) would not change.

Great Lakes

The Great Lakes contain 18% of the world's supply and 95% of the U.S. supply of surface freshwater, and they are an important source of commerce and recreation for the region. In recent years, reductions in pollutant loadings have significantly improved the quality of such water bodies as Lake Erie. The Great Lakes States produce 59% of the country's corn and 40% of its soybeans, and their forests have important commercial, recreational, and conservation uses.

Models were used to estimate the potential impacts of climate change on lake levels and ice cover. Results from these studies were used to analyze impacts on navigation and shorelines. Changes in the thermal structure of the Central Basin of Lake Erie and southern Lake Michigan were estimated. Output from these studies was used along with scenario temperatures to analyze potential impacts on fishes in the lakes. Changes in crop yields were estimated for corn and soybean, and changes in forest composition were analyzed for Michigan and Minnesota (see Figure 13).



Lakes
Climate change could:
- cause average lake levels to fall by 0.5 to 2.5 meters
- reduce ice cover duration by 1-3 months

Adjustments may be required including:
- increased dredging of harbors and channels, or
- lower cargo capacities on ships

Water Quality
Changes in temperature and precipitation could cause:
- greater stratification in lakes and increased growth of algae, which in turn could cause lower dissolved oxygen levels in shallow areas
- an increase in pollutants resulting from more dredging

Wetlands and Fisheries
Higher temperatures could cause:
- an increase in fish habitats in fall, winter, and spring, and a decrease in summer
- accelerated growth for some fish species
- potential invasion by new species

Forests
Higher temperatures could result in:
- loss of mixed northern hardwood and oak in southern areas
- shifts of mixed northern hardwood and boreal forests in northern areas to all northern hardwood
- forest declines evident in 30 to 60 years

Agriculture
Higher temperatures could cause:
- corn and soybean yields to increase in North, decline in Cornbelt; mixed results under climate change and CO2
- acreage could expand in the North, leading to increased erosion and runoff

Figure 13. Great Lakes

Lake Levels Could Drop and Ice Cover Duration Could Decrease

Higher temperatures would likely reduce snowpack and could increase evaporation, which would lower lake levels. The level of Lake Superior was estimated to be reduced under the climate scenarios by0.4 to 0.5 meters (1.2 to 1.5 feet), and that of Lake Michigan by 0.9 to 2.5 meters (3 to 8 feet). Diversions out of the lakes for irrigation or to supply other basins would further lower lake levels, although these impacts were not analyzed. These results are very sensitive to assumptions made about evaporation and under some circumstances, lake levels could rise.

Higher temperatures would also reduce ice cover on the lakes. Specifically, they could cut ice duration by 1 to 3 months on Lake Superior and by 2 to 3 months on Lake Erie, although ice still would form on both lakes. Changes in windspeed would affect the reduction in duration of ice cover. In response to lower lake levels, either ships would have to sail with reduced cargoes or ports and channels would have to be dredged. On the other hand, a shorter ice season would allow a longer shipping season.

Water Quality May Be Degraded in Some Areas

Higher temperatures could lengthen stratification of the lakes (where summer temperatures warm the upper part of lakes and isolate the cooler lower layers of lakes). Analysis of the Central Basin of Lake Erie showed that longer stratification, combined with increased algal productivity, would most likely reduce dissolved oxygen levels in the lower layers of the lake (see Figure 14). Reducing pollutant loadings in the lake would likely result in less severe impacts. One study raised the possibility that the annual mixing of a lake such as Lake Michigan may be disrupted. If winds and storms increased, such outcomes would be less likely. Disposal of contaminated dredge soils could increase water pollution.

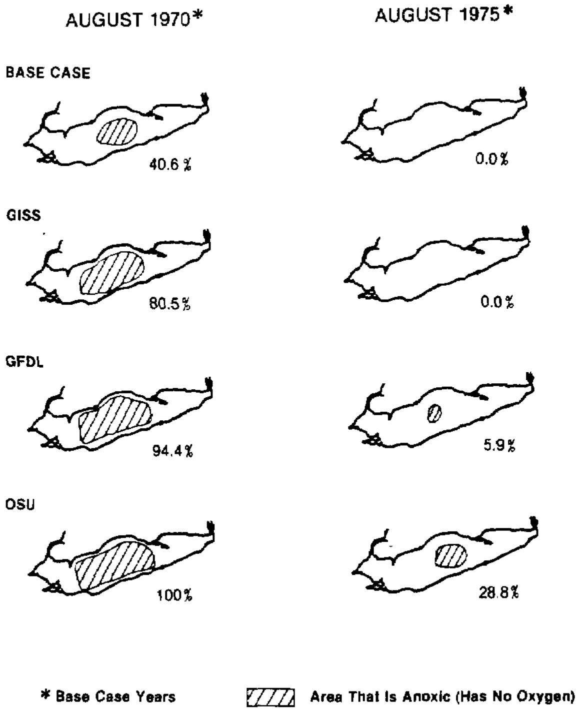


Figure 14. Area of central basin of Lake Erie that becomes anoxic under doubled CO_2 scenarios.

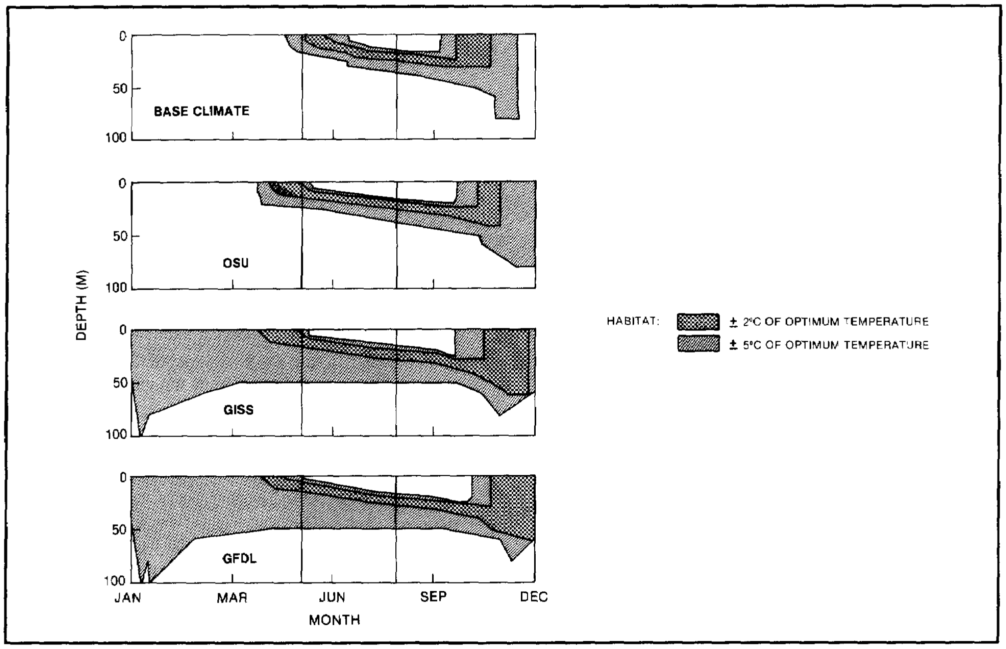


Figure 15. Increases in thermal habitat for lake trout in southern Lake Michigan under alternative climate scenarios.

Fish Productivity in Open Areas May Increase

The average annual thermal habitat would increase with a warmer climate (see Figure 15). If sufficient oxygen is present, growth rates and productivity for such fish as bass and lake trout in open areas of large lakes may increase, provided that the forage base also increases. However, reduced ice cover and decreased water quality could harm some species in shallow basins of the Great Lakes. The effects of increased species interaction, changes in spawning areas, and possible invasion of exotic species were not analyzed.

Northern Agriculture May Benefit

As a result of the relative increase in northern agricultural productivity, agriculture could be enhanced in Minnesota, Wisconsin, and northern Michigan with additional opportunities for the agriculture support sector. The presence of relatively poor soils, however, could limit agricultural expansion. Increased cultivation in northern areas could increase erosion and runoff, with negative impacts on surface and groundwater quality.

Abundance and Composition of Forests Could Chance

Northern hardwood forests in dry sites in Michigan may die back and could become oak savannas or grasslands. In northern Minnesota, mixed boreal and northern hardwood forests may become completely northern hardwoods. Productivity in some wet sites in Michigan could improve. Commercially important softwood species could be replaced by hardwoods used for different purposes. Changes in forests could be evident in 30 to 60 years. Whether reforestation with southern species not currently in the region and CO_2 fertilization would mitigate these impacts was not studied.

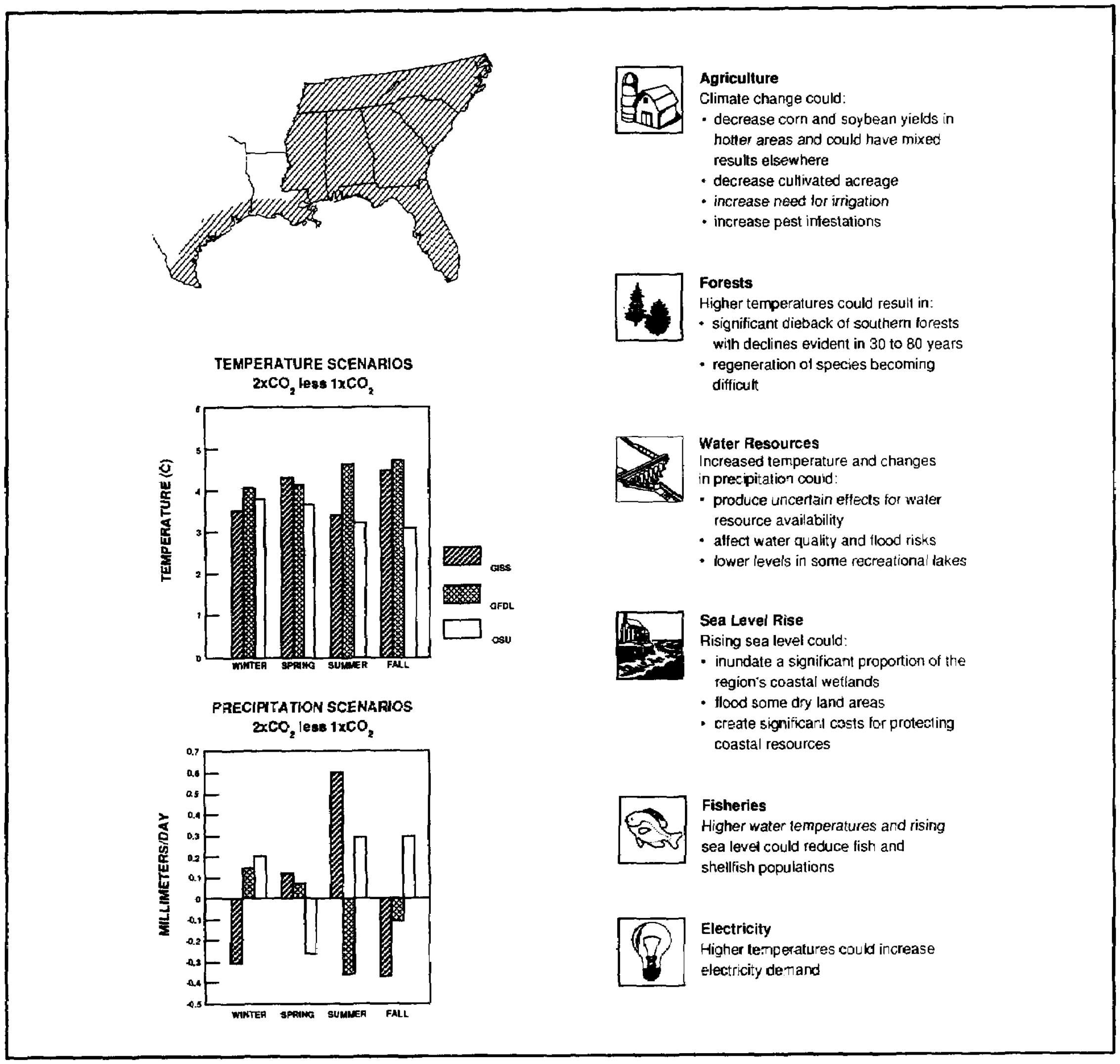
Southeast

The Southeast is distinguished from the other regions in this study by its warm temperatures, abundant rainfall, large coastal plain, and productive marine fisheries. The region supplies about half of the nation's softwood and hardwood timber, and tobacco, corn, and soybeans are among its major crops. Over 85% of the nation's coastal wetlands are in the Southeast, and over 43% of the finfish and 70% of the shellfish harvested in the United States are caught in the region.

This report focused on two regions within the Southeast: the Tennessee Valley and the Chattahoochee and Apalachicola Rivers. The Tennessee Valley Authority examined the potential vulnerability of its water management system to high and low riverflow scenarios (based on runoff estimates from GCMs). Flow in the Chattahoochee River Basin was estimated using hydrologic analysis to study impacts on the management of Lake Lamer, which supplies water to Atlanta. The estimates of outflow from the lake, along with estimates of the flow in the Apalachicola River, were combined with potential wetland losses attributable to sea level rise to identify impacts on finfish and shellfish in Apalachicola Bay. Sea level rise impacts for the entire Southeast were derived from the national studies. Crop yields were estimated for corn and soybeans, and changes in forest composition were analyzed at several sites across the region (see Figure 16).

Adverse Impacts on Agriculture and Forest Could Hurt the Region

Decreases in the relative productivity of southeastern agriculture were estimated under the scenarios that lead to the abandonment of 10 to 50% of the agricultural acreage in the region. The studies did not consider introduction of new crops, such as citrus, or the use of new technologies, such as biotechnology.



Agriculture
Climate change could:
- decrease corn and soybean yields in hotter areas and could have mixed results elsewhere
- decrease cultivated acreage
- increase need for irrigation
- increase pest infestations

Forests
Higher temperatures could result in:
- significant dieback of southern forests with declines evident in 30 to 80 years
- regeneration of species becoming difficult

Water Resources
Increased temperature and changes in precipitation could:
- produce uncertain effects for water resource availability
- affect water quality and flood risks
- lower levels in some recreational lakes

Sea Level Rise
Rising sea level could:
- inundate a significant proportion of the region's coastal wetlands
- flood some dry land areas
- create significant costs for protecting coastal resources

Fisheries
Higher water temperatures and rising sea level could reduce fish and shellfish populations

Electricity
Higher temperatures could increase electricity demand

Figure 16. The Southeast

Most forests in the Southeast were estimated to have difficulty surviving the assumed climate change. Dieback of existing forests in such areas as Georgia and Mississippi could be particularly large. These changes could be evident in 30 to 80 years. The forest studies did not consider whether more southern species could be transplanted and survive in the region, nor did they account for higher CO_2 concentrations, which could mitigate some losses. The combined effects of reduced agriculture and forestry could lead to significant economic losses in the Southeast.

Some Coastal Fish Species Would Be Harmed

Sea level rise could inundate most of the coastal wetlands and raise salinity levels, which could reduce the populations of gulf coast fisheries. In addition, higher temperatures may exceed the thermal tolerances of many species of shellfish in gulf coast estuaries, further reducing fish populations. Whether these species would be able to migrate to cooler water was not considered. Some species, however, could increase in abundance, while others may migrate into the region.

The Studies Were Unable to Determine Regionwide Impacts on Water Resources

The Southeast currently has little winter snowcover. Therefore, seasonal runoff depends much more on changes in rainfall than on changes in temperature that affect the size of snowpack. Analysis of the rivers managed by the Tennessee Valley Authority showed that increased runoff could lead to higher riverflow and higher flood probabilities, while less runoff could reduce flood probabilities, but could lead to lower riverflow and problems maintaining adequate supplies for industrial use, powerplants, and dilution of effluent. Use of climate change scenarios produced inconclusive results concerning the potential change in flow in the Chattahoochee River. A study of the management of Lake Lanier concluded that changes in operating rules would be sufficient to handle higher or lower flows estimated in the scenarios, although some uses would be restricted.

The Great Plains

Agriculture is one of the main sources of income in the Great Plains. The States of Kansas, Nebraska, Oklahoma, and Texas produced 80% of the nation's sorghum and 30% of the wheat crop in 1982. In recent years, increased use of water from the Ogallala Aquifer has reduced groundwater levels in the region, with potential long-term consequences for agriculture and the economy.

The studies in this report focused on Nebraska, Kansas, Oklahoma, and Texas, and concentrated mainly on agriculture-related impacts. They estimated changes in corn, wheat, and soybean yields and in the demand for irrigation. Changes in runoff and leaching of chemicals from farms were also examined (see Figure 17).

Crop Acreage Could Decline

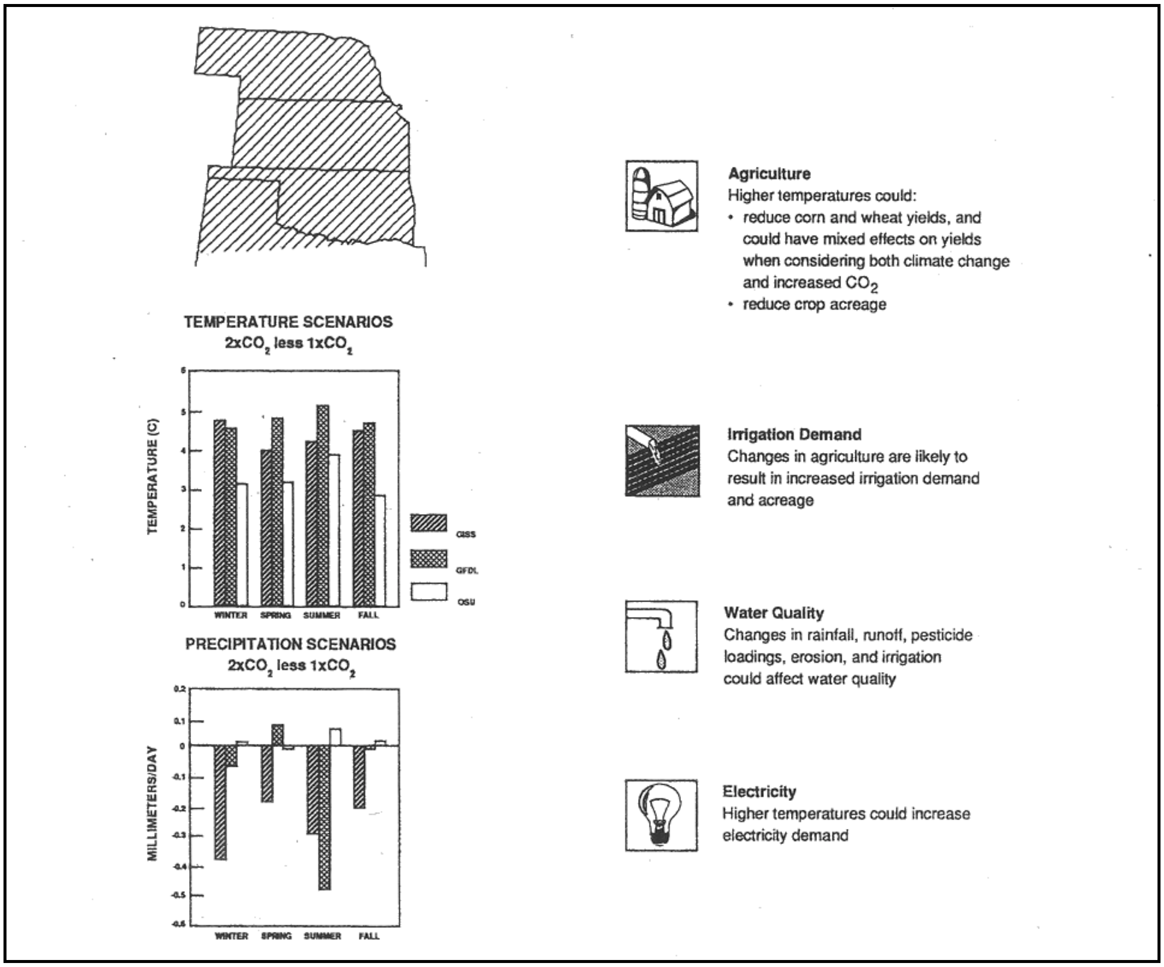
The crop yield and economic adjustment studies indicate that grain crop acreage could diminish in the region. The direction of changes in wheat and corn yields depends on the direct effects of CO_2 on crop growth and the severity of climate change. If climate becomes hotter and relatively drier, yields could decrease. Whatever the climate change, relative productivity may decline compared with northern areas. As a result, crop acreage was estimated to drop by 4 to 22%. Such a reduction in agriculture could adversely affect the economy of the region. These studies did not consider use of new technologies or introduction of new crops.

Demand for Irrigated Acreage Would Increase

The demand for irrigation on the farms that continue to grow grain crops could increase. Irrigated acreage, which currently makes up about 10% of the total acreage and is growing, could increase by S to 30%. This report did not examine how this demand would be satisfied, although the Ogallala Aquifer could be a candidate. Other impacts of global warming could change ground and surface water supplies and, possibly, surface water quality. Changes in precipitation could affect the leaching of pesticides into groundwater and runoff to surface waters in some cases, although the direction of change cannot be determined because runoff and leaching of pesticides and soils are very sensitive to rainfall variability.

FINAL THOUGHTS AND POLICY IMPLICATIONS

Because this is the most comprehensive study to address the issue of the environmental effects of climate change in the United States, we expect that a sizable debate will follow its publication. Considerable



Agriculture
Higher temperatures could:
- reduce corn and wheat yields, and could have mixed effects on yields when considering both climate change and increased CO_2
- reduce crop acreage

Irrigation Demand
Changes in agriculture are likely to result in increased irrigation demand and acreage

Water Quality
Changes in rainfall, runoff, pesticide loadings, erosion, and irrigation could affect water quality

Electricity
Higher temperatures could increase electricity demand

Figure 17. The Great Plains.

additional research and analyses are likely to amplify, improve, and challenge these findings. We expect further research to develop new insights into the role of climate, but precise forecasts must await more advanced climate models, which may require many years to develop. For some time to come, our ability to provide national and local officials with guidance may be limited to effects driven primarily by temperature and sea level changes.

Apart from strategies to limit emissions of greenhouse gases (discussed in the companion report), policymakers should consider policy options for adapting to global warming. Consideration of these options is complicated by the uncertainties identified in this report by delays in the onset of climate change, and by the pressure to solve today's problems. Many adaptations would undoubtedly occur as climate changes, but some decisions being made today have a long enough lifetime and sufficient risk to support consideration of the potential range of impacts of the greenhouse effect. These decisions should be made if they make economic and environmental sense for today's conditions and are sufficiently flexible to handle changing climate. Given the uncertainty about the timing, magnitude, and regional scope of climate change, we cannot plan for specific climate conditions in the future, but we can strive to be ready to respond to significantly changed climate conditions in the future.

Conversely, natural resource management should not assume that climate will not change. All managers of natural resources that are sensitive to climate should consider the vulnerabilities of their systems to climate change and whether anticipatory steps are prudent. In some cases, no anticipatory action would be needed -- the systems can be adjusted and adapted as climate changes. In other areas, where long-term decisions on sensitive systems may result in irreversible impacts, anticipatory actions to mitigate these potential effects may be required. It may make sense in some instances to change the rules under which long-term planning is done, such as zoning laws, to allow for consideration of climate change in private sector decisions. Finally, research and education are needed in many areas to improve our ability to respond to these changes. In any case, managers should reexamine their systems to consider ways to improve the flexibility and resiliency of the systems to handle these and other changes. The criteria to guide decisions should include consideration of the following factors:

- the uncertainties in the magnitude and timing of effects;
- whether the lifetime of the plan, project, or policy is long enough to be affected by climate change;
- whether effects of climate change are irreversible;
- whether the policy or project will increase flexibility and resilience or restrict future options;
- whether a policy or action makes economic or environmental sense, even without climate change;
- the uniqueness of the ecosystems or manmade structures that may need protection; and
- whether the impacts would be greater if no anticipatory action were taken.

The US. government is strongly supporting the Intergovernmental Panel on Climate Change (IPCC) under the auspices of the United Nations Environment Programme and the World Meteorological Organization. The IPCC has established a process for governments to follow when reviewing scientific information and policy options. The federal government is conducting other activities on global climate change. The Global Climate Protection Act of 1987 calls for a scientific assessment of climate change, which is to be completed by 1989. This work will be sponsored by EPA and other federal agencies such as the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the National Science Foundation, and coordinated through the IPCC. Also, the Department of Energy and EPA have been asked to report to Congress on policy options for reducing CO_2 emissions in the United States. In addition, various federal agencies conduct significant research programs on climate. These research efforts on climate change are coordinated by the National Climate Program Office and the Committee on Earth Sciences. The latter has produced a plan called Our Changing Planet: A United States Strategy for Global Change Research, which outlines federal research activities.

The federal government can also take the lead in pursuing prudent policies in anticipation of climate change, and many agencies can play a role in preparing the country for the impacts. These include the Departments of the Interior, Energy, Health and Human Services, and Agriculture; the U.S. Environmental Protection Agency; and the U.S. Army Corps of Engineers (see box on "Federal Activities"). However, adaptation should not occur just at the federal level, for there will likely be a need to involve other nations, state and local governments, industry, and even individuals. The regional studies in this report demonstrate that climate change cuts across manmade and natural systems, geographic boundaries, and government agencies. Research, technical guidance, planning, and creative approaches to resource management will be needed in the future to prepare for the impacts of climate change on the United States.

FEDERAL ACTIVITIES THAT SHOULD CONSIDER CLIMATE CHANGE

Sample questions relating to climate change impacts that federal agencies should consider:

Agency	Policy Questions
U.S. Environmental Protection Agency	How should current wetlands protection programs be modified to accommodate future sea level rise and precipitation changes? Should regulatory approaches to air pollution be supplemented with incentive systems, new chemicals, or relocation policies?
U.S. Department of the Interior	Should national parks and wildlife refuges purchase land to accommodate the migration necessitated by climate change? Should additional parks and refuges be created? Are current activities increasing the vulnerability of species that might be threatened by climate change? Should the U.S. Geological Survey produce coastal area maps with finer contour levels? How will climate change alter projected groundwater levels? Will current water policies in the West prove to have been ill-advised if the climate changes?
U.S. Department of Agriculture	Do price support programs help or hinder the adjustments that climate change may necessitate? To what extent could irrigation be increased on a sustainable basis if climate became drier? What actions would be necessary to maintain national forests as the climate changes?
U.S. Army Corps of Engineers	How does a consideration of future climate change alter the relative merits of alternative approaches to coastal protection, flood control, and navigation? Will climate change affect the successes of wetlands protection efforts in Louisiana as administer under Section 404 of the Clean Water Act?
Federal Emergency Management Agency	Will current rate caps on premiums enable the National Flood Insurance Program to remain solvent if the climate changes?
U.S. Department of Health and Human Services	Are current programs adequate to address potential changes in mortality and shifts in diseases resulting from climate change?

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CHAPTER 1
INTRODUCTION

by Joel Smith

Since the beginning of the Industrial Revolution, human activities have led to increased concentrations of greenhouse gases in the atmosphere. Fossil fuel burning, which releases CO_2, CO, N_2O, and other pollutants, has expanded many times over. Changes in agriculture have led to increased emissions of CH_4 and N_2O. Population growth has contributed to deforestation in many areas of the globe, which in turn has affected the global carbon cycle. Atmospheric concentrations of tropospheric ozone and chlorofluorocarbons have also increased, primarily because of industrial activity.

Scientists have concluded that the increase in greenhouse gas concentrations will eventually change global climate. In 1979, the National Academy of Sciences stated that a doubling of carbon dioxide levels would lead to an increase of 1.5 to 4.5°C (2 to 8°F) in global air temperatures. Since then, other researchers have examined the increase in all greenhouse gases and have concluded that a greenhouse gas increase equivalent to CO_2 doubling could occur as early as the 2030s, with a hypothesized commensurate global warming lagging by several decades.

The Earth's atmosphere has undergone many cycles of warming and cooling in the past. Paleoclimatologists have estimated that at the glacial maximum of the last ice age, which was about 18,000 years ago, the Earth was approximately 5°C (9°F) cooler than at present. This is generally attributed to changes in orbital characteristics combined with lower trace gas concentrations and different climate feedbacks.

Two aspects may make the current greenhouse warming different from past climate changes. First, it will raise temperatures higher than the planet has experienced in the last 125,000 years. (During the Pliocene Epoch (2 to 5 million years ago), global temperatures were several degrees higher than they are now.) Second, past climate changes of comparable magnitude have generally occurred over tens of thousands of years. Estimates are that the greenhouse effect may raise atmospheric temperatures several degrees in less than a century.

CONGRESSIONAL REQUEST FOR REPORTS

The significant implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years, Members of Congress have held hearings and have begun to explain the implications for public policy. Thus interest was accentuated during a series of hearings held in June 1986 by the Senate Subcommittee on Pollution of the Environment and Public Works Committee. Following the hearings, members of the Senate Environment and Public Works Committee sent a formal request to the EPA Administrator, which asked the Agency to undertake two studies on climate change due to the greenhouse effect. (The letter is reprinted in Appendix C of this report.)

One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

Congress also requested that EPA prepare a study on policy options to stabilize current levels of atmospheric greenhouse, gas concentrations. That study analyzes policy options for limiting gas concentrations including energy efficiency, alternative technologies, reforestation options, chlorofluorocarbon (CFC) reductions, and other options for limiting CH_4 and N_2O. It is entitled *Policy Options for Stabilizing Global Climate* and is a companion to this report. Congress requested the studies in the Fiscal Year 1987 Continuing Resolution.

GOALS OF THIS REPORT

This report builds on the past contributions of many scientists throughout the world, most notably the reports by the National Academy of Sciences (1979, 1983, 1987), the World Meteorological Organization and the International Council of Scientific Unions (1986), the United Nations Environment Programme (1986), Scope 29 (1986), and the U.S. Department of Energy (1985a,b). It is an attempt to identify some of the sensitivities, direction and magnitude, linkages, regional differences, national impacts, policy implications, and uncertainties associated with the effects of global climate warming.

We hope it will provide useful information to climate modelers and effects researchers. We also hope that officials, at all levels of government, will be encouraged to examine the implications of climate change for long-term policies. Since this is the first study of this type, we expect that a great deal more research, analysis, and planning will be needed in the future. We do not pretend to have all the answers.

This report has been designed to identify the following:

Sensitivities

Since the rate and extent of climate change on a red level are uncertain, we cannot predict effects. However, we can identify the sensitivities of systems to climate change. Our goal was to use a variety of scenarios to determine what climate variables are important in causing impacts and the degree to which systems are sensitive to changes in these variables. Specifically, we were interested in identifying the sensitivity of systems to higher temperatures and sea level, which are among the changes most likely to occur following increased greenhouse gas concentrations. (For further discussion, see Chapter 2: Climate Change.)

Direction and Magnitude

Since the scenarios do not encompass all possible combinations of climate change due to increased greenhouse gases, the results do not represent the entire range of possible effects. For example, there could be more or less rainfall, or higher or lower temperatures than estimated by climate models. Yet, the results from various scenarios help define the direction and magnitude of effects. First, we examined them to see if a direction of change (e.g., more water, lower crop yields) is evident. Second, we attempted to determine if the magnitude of change is significant. Third, we asked whether the results are consistent with scientific theory. Outcomes outside the bounds of our results cannot be ruled out at this time.

Linkages

Individual environmental systems will not be affected by climate change in isolation. Water resources, for example, may be affected not only by changes in water supply but also by changes in demand for water for such purposes as irrigation. Wildlife may be directly affected by changes in climate and indirectly affected by changes in habitat due to climate change. This report attempts to identify linkages among effects, quantitatively where possible and qualitatively elsewhere. Linkages are identified mainly in regions. Quantitative analysis of all linkages would change the numerical results of this report, in many cases exacerbating impacts.

National Impacts

Impacts were analyzed on a national scale to see how the country as a whole may be affected by climate change and to see if latitudinal patterns (such as northward shifts in species) are detectable. Some analyses, such as coastal wetland impacts and changes in electricity demand, were conducted on a national basis. Other national analyses, such as forests, were based on results from regional studies. In some cases, national analyses estimated total costs over the next century. No attempt was made to assess the total national impact from climate change, and conclusions about the total costs and benefits of climate change should not be made.

Regional Impacts

Effects were examined in several regions of the United States for a number of reasons. As pointed out above, linkages exist among many of the effects, and these are likely to be seen on a regional scale. For example, the supply of water in a river basin may change as a result of climate change. The water resource in that basin may also be affected by changes in the demand for water for irrigation, powerplant cooling, and other uses. Analysis of similar systems in different regions allows for comparison of impacts among regions. This report, however, does not attempt to identify "winners and losers."

Uncertainties

Many uncertainties are related to our knowledge about the rate and magnitude of warming and changes in regional weather patterns. As discussed in Chapter 2: Climate Change, we do not know how much and how quickly climate may change and how regional climates may change. Uncertainties also exist about how ecological and other systems will be affected by climate change. We do not have empirical evidence on how these systems will respond to higher temperatures and CO_2 levels, as well as to different rainfall amounts. These uncertainties are reflected in the models used to estimate climate change and impacts. This report attempts to clearly state these limitations.

Policy Implications

The management of most natural resources has generally been undertaken assuming that climates will not change. A change in climate could affect many of these resources and raise implications for resource management. This report discusses some policy implications of climate change, but it does not lay out a prescriptive policy agenda.

Research Needs

The analysis in this report should provide climate modelers with information concerning how general circulation models could be improved. It should also help define research needs for future analysis of the potential impacts of climate change.

Fundamentally, these goals center on the identification of important issues and state-of-theart science investigations in each environmental system. Because each component of science and policy development is at an early stage, the goals of the report are to develop insights and estimates of the ranges of possible future effects and to use that information for identifying where the policies and research programs of EPA and other agencies should be reexamined.

STRUCTURE OF THE ANALYSIS

Important Systems

This report focuses on the following systems, which are important, are sensitive to climate, and may be particularly affected by climate change:

Forests
Agriculture
Sea Level Rise
Biodiversity
Water Resources
Electricity Demand
Air Quality
Human Health
Urban Infrastructure

Regional Case Studies

Four regional case studies were selected: the Southeast, the Great Lakes, California, and the southern Great Plains. These regions were picked because each is important for economic, social, and environmental reasons, and each offers some unique current characteristics that make it an interesting example of the range of possible environmental issues that may need to be considered. The Southeast depends heavily on forestry and agriculture, and has extensive and fragile wetlands and coastal ecosystems. The Great Lakes are the dominant natural resource in their region, supplying freshwater, fishery resources, and a pathway for shipping and transportation, and providing a natural laboratory for environmental issues that affect both the United States and Canada. California already must carefully manage its water supplies, and its agricultural industry provides many crops for the United States and a large share of the international market; it is among the most productive agricultural regions in the world. The Great Plains is one of the largest producers of grain crops in the world. Although these regions are diverse, they do not encompass the entire range of regional differences in the United States. The analysis of effects in these regions does not cover all potential impacts in the United States.

National Studies

The effects on a number of systems were quantitatively analyzed on a national scale. National agricultural markets were analyzed with respect to their sensitivities to changes in yield derived from our agricultural models. Options for adapting to a sea level rise were examined on a national scale, as were possible health impacts. Forestry, water management, air quality, and biodiversity issues were explored by analyzing the results of several of the regional case studies with a broader perspective. In each case, the national-level analyses provide an additional level of qualitative integration that a purely regional analysis could not. The structure of the regional and national studies is displayed in Figure 1-1.

ANALYTIC APPROACHES

Since we do not know how climate will change, this report used scenarios of possible climate change to identify sensitivities of systems to climate. The climate scenarios we used were based on outputs from general circulation models (GCMs) (see Chapter 4: Methodology). Where possible, we tried to obtain quantitative estimates of effects. However, the development of quantitative estimates was constrained by the availability of well documented models that included some interaction of the particular effect in question and climatic variability. We obtained additional information on sensitivities by reviewing the literature and by gathering expert judgment. The approach of using existing models, all of which were originally constructed for other purposes, makes the interpretation of results instructive but somewhat limited with respect to the full range of climatically relevant questions that could be asked.

PROCESS FOR CONDUCTING THIS REPORT

We used an eight-stage process to define the scope of this report, select the projects, write the chapters, and review the results.

Step 1: Initial Scoping of the Report

This stage immediately followed the request from the Senate Environment and Public Works Committee. We agreed on using the regional case study approach, on the four regions to be investigated, and on using climatic scenarios. We also decided not to attempt to analyze environmental effects outside the United States in this report. Our rationale for this decision was based on available time and funds, and on the lack of suitable models that would be immediately accessible to us.

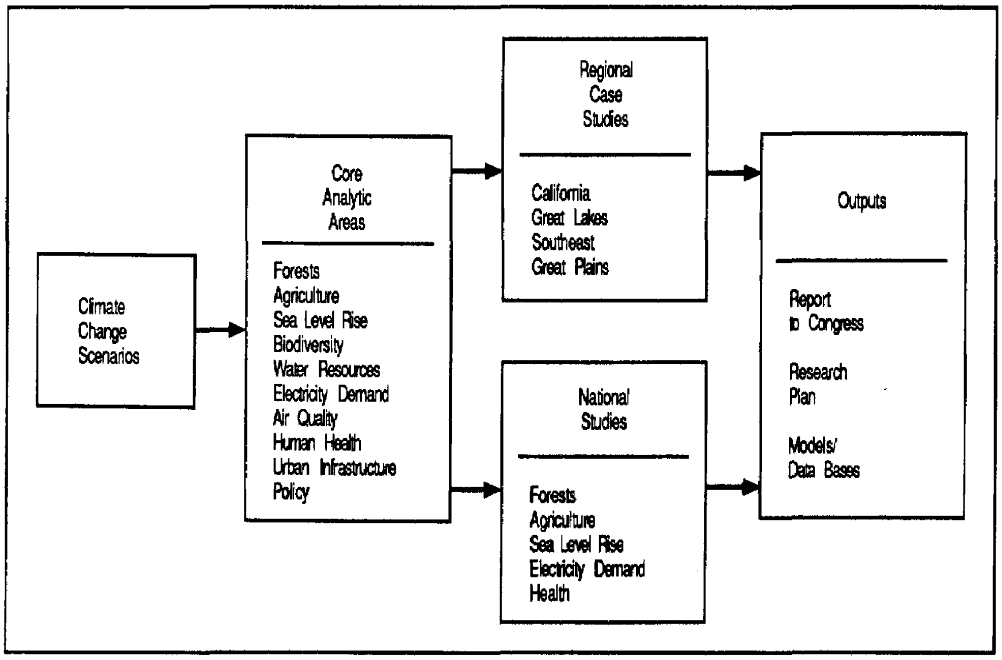

Figure 1-1. Elements of the effects report.

Step 2: Preparatory Workshops

We held two workshops in February and April 1987 in Boulder, Colorado, to prepare the report. In the February workshop, sponsored and organized by the National Center for Atmospheric Research, general circulation modelers convened to discuss some of the problems inherent in attempting to understand the regional results from global models. Several major topics were discussed from the standpoint of how the results from GCMs should be used in impact studies. A list of variables that would be available for use by effects researchers was produced at the end of the workshop. In addition, several potential studies on aspects of the frequency of extreme weather events were identified.

The April workshop was organized with the assistance of the University of Colorado. Approximately 100 scientists explored the major climate change-related issues in agriculture, forest effects, water resources, and sea level rise. Working groups in each discipline discussed the potential impacts that climate change might have and the most important uncertainties to explore to arrive at better predictions. The working groups were then rearranged into regionally oriented groups. They identified a series of studies that would address the major scientific issues in each region.

Step 3: Identification of Potential Projects

From the lists identified in the two Boulder workshops, and from additional studies on urban and regional air quality subsequently identified internally by EPA, we arrived at list of investigators from whom we would solicit proposals. The decision to solicit proposals was based primarily on the potential coverage of environmental issues in each region.

Step 4: Reviews of Proposals

At least one intramural and two extramural reviewers examined each proposal. We responded to all comments and modified proposals as appropriate. EPA used a combination of cooperative agreements, existing contracts, and interagency agreements to fund projects for this report.

Step 5: Planning and Integration

All the researchers met with EPA staff in October 1987 to discuss scenarios, goals, and approaches for the studies. Researchers discussed integration of projects within regions as well as the commonality of approaches within disciplines.

Step 6: Analysis

The National Center for Atmospheric Research assembled the scenarios and distributed them to researchers in the fall of 1987. Researchers conducted their analysis over the winter and prepared draft reports in March and April 1988.

Step 7: Preliminary Project Review

In April 1988, EPA assembled panels of scientists to provide a preliminary review of most of the agriculture, forestry, and hydrology projects. The principal investigators of the appropriate projects were asked to present their work orally and in written drafts. EPA project managers used the comments from the review panels to make corrections in the conduct of a few projects, and as a guide to interpreting the results of individual projects and to writing this report.

Step 8: Project and Report Peer Review

At least two to three peer reviewers examined the final reports from all principal investigators before the EPA project managers accepted them. During this time, EPA staff on the report project team wrote the overviews that are reflected in this final report. In November 1988, a special subcommittee of EPA's Science Advisory Board (SAB) was convened and asked to review the entire report. Following the SAB's written review, the EPA project team responded to comments and produced the final version of the Effects Report. The draft of the report was sent to other federal agencies and the Office of Management and Budget for review and comment, and these comments were also taken into account in the final version

STRUCTURE OF THIS REPORT

This report is divided into several sections. Section I consists of Chapter 2 on trends in emissions of greenhouse gases and potential impacts on climate; Chapter 3 on changes in variability; and Chapter 4 on the choice of scenarios and effects modeling. In Section II, the results of national analyses are presented. Each chapter covers a different system. The chapters include an overview of relevant regional studies, and they present results from national analyses. Each chapter discusses the current state of resource, reviews previous literature on climate change and the resource, discusses studies used for this report, presents national results from regional and national studies, and discusses broader socioeconomic and policy implications. The design and limitations for each study are presented only once -- in a regional chapter if it is a regional study or in a national chapter if it is a national study. Section III contains results from the regional case studies, with each chapter devoted to different regions. Each regional chapter describes the climate-sensitive systems in the region; reviews previous studies on impacts of climate change on the region; describes the structure of regional studies for the report; discusses regional climate change scenarios; reviews the design, results, and limitations of the studies; and discusses the broader socioeconomic and policy implications of climate change for the region. The regional chapters include relevant regional results from national studies. Not all regionally relevant results are presented in the appropriate regional chapters. Results for health are presented only in the health chapter in Section II. Section IV includes conclusion chapters. Chapter 18 discusses directions for future research on climate change effects, and Chapter 19 discusses policy implications and recommendations.

This report is designed to be an overview of the individual studies. Those studies are printed in appendix volumes. In this report, the studies are referenced by the author's name or names in parentheses and volume letter. Previously published work is referenced by the author's name and the year of publication.

RELATIONSHIP TO CURRENT NATIONAL AND INTERNATIONAL ACTIVITIES

National Research and Policy Activities

The Global Climate Protection Act of 1987 requested EPA to develop a national policy on global climate change and to prepare an assessment of scientific information. The very scope of this issue suggests that this request can be fulfilled only in cooperation with other federal agencies; hence, EPA is working with these agencies to formulate a process to achieve this goal. The scientific assessment will be conducted in coordination with the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation, and other agencies. To the extent possible, this scientific assessment will also be developed on an international basis and should be available in 1990.

The development of a national policy will be coordinated with the Department of Energy and other natural resource departments. The goal will be to build on this report and others under development by federal agencies to identify the adoptive policies and other measures that may be appropriate to deal with this issue. The nature of this issue suggests that a continuous review of domestic policy will be required for many years.

International Activities

In 1987, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) were asked by member governments to establish an Intergovernmental Panel on Climate Change (IPCC) for the specific purpose of reviewing the scientific information and potential response strategies. The WMO has primary responsibility for the World Climate Research Programme, and UNEP has responsibility for the World Climate Impacts Programme. The UNEP was the primary international agency responsible for negotiations leading to the Montreal Protocol To Protect the Ozone Layer. The first meeting was held in November 1988, and subsequent meetings have been held in 1989 to organize activities. It is expected that the IPCC will be the primary forum for multilateral discussions between governments on this issue.

Other governments and international agencies are also examining this issue. Italy, Japan, and the Netherlands held conferences in 1989. The United States has bilateral activities with the Soviet Union and China The Organization for Economic Cooperation and Development and the International Energy Agency are examining their potential contributions.

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CHAPTER 2
GLOBAL CLIMATE CHANGE

by Alan Robock

The Earth's climate has changed continuously over the entire lifetime of our planet as a result of various natural causes. Recently, we have come to the realize that human activities may, in the near future, produce effects powerful enough to overwhelm these natural mechanisms and dominate the changes of climate. By early in the next century, the planet's temperature may rise to a range never before experienced by our species, at a rate faster and to temperatures warmer than the Earth has experienced in the past million years. This anticipated temperature increase would be caused by an enhancement of the greenhouse effect.

Although the overall effect of increased greenhouse gases is understood, many details are less clear, including both the timing of the predicted warming and its spatial distribution. This is because the response of the climate system to the additional greenhouse gases, including all the feedbacks and interactions that would take place, is very complicated and not completely understood. In addition, while the human-induced component of the greenhouse effect increases in magnitude, other causes of climate change remain important, such as changes in the amount of energy emitted by the sun, changes in the atmospheric composition due to volcanic eruptions and human input of aerosols, internal redistributions of energy by El Niños, and random, unpredictable variations. Thus, the task of predicting the future evolution of climate involves not only understanding the response of the climate system to increased concentrations of greenhouse gases but also predicting the concentrations of these gases and the effects of other causes of climate change.

Several detailed assessments of the current state of our knowledge of these projected climate changes have been conducted recently. These include studies by the National Research Council (NRC, 1979, 1983, 1987), the World Meteorological Organization (1986a,b), and the "state-of-the-art" reports of the Department of Energy (MacCracken and Luther, 1985a,b; NRC, 1985; Trabalka, 1985; Strain and Cure, 1985; White, 1985). Excellent shorter summaries include Ramanathan (1988) and Chapters 2 and 3 of Lashof and Tirpak (1989). These studies should be consulted for more detailed information.

This chapter describes the climate system, the important causes of climate change for the next century, and the so-called climate forcings, and it summarizes the various trace gases that human activities put into the atmosphere. It then describes important feedbacks in the climate system that act to amplify or dampen the climate change induced by the forcings. Uncertainties in our understanding of these

The Greenhouse Effect

Gases in the atmosphere are virtually transparent to sunlight (shortwave radiation), allowing it to. pass through the air and to heat the Earth's surface. The surface absorbs the sunlight and emits thermal radiation (longwave radiation) back to the atmosphere. Because several gases in the atmosphere, particularly water vapor (H_20) and carbon dioxide (CO_2), are not transparent to the outgoing thermal radiation, they absorb some of it and heat. the atmosphere. The atmosphere emits thermal radiation, both upward to outer space and downward to the surface, further warming the surface.

This phenomenon is called the greenhouse effect because in some respects it describes how an actual greenhouse works. Even without any human impacts, this natural greenhouse makes the Earth's surface about 33°C (59°F) warmer than it would be without the atmosphere. Gases that are transparent to sunlight, but not to thermal radiation, are called greenhouse gases.

If either the concentration of existing greenhouse gases increases or greenhouse gases that were not there before are added to the atmosphere, more thermal radiation will be absorbed and re-emitted downward, making the surface warmer than before.

feedbacks are an important component of our current uncertainty of the timing and amount of future climate change. Next, it discusses the recent history of climate change, compares these observations with theory, and presents theoretical models of the climate and their projections of future climate change. Finally, the concluding section summarizes the extent of our knowledge about the future climate and discusses future research needs.

THE CLIMATE SYSTEM

The climate system includes all the interactive components of our planet that determine the climate. This includes the atmosphere, oceans, land surface, sea ice, snow, glaciers, and biosphere. Climate change can be measured in terms of any part of the system, but it is most convenient to use surface air temperature as a measure of climate, since it is the parameter for which we have the best record, and it is measured where the most important component of the biosphere -- humans-- lives. Other components of the climate system, such as precipitation, cloudiness, evaporation, windspeed and direction, and sea level, also have important impacts on human activities.

Figure 2-1 shows a schematic representation of the climate system. Changes in the amount of energy emitted by the sun, changes in the atmospheric composition (such as from volcanic eruptions and human input of aerosols and greenhouse gases), and changes in the Earth's surface (such as deforestation) can affect the Earth's energy balance. Atmospheric and oceanic circulation can redistribute the energy.

The radiative balance of the planet, as shown in Figure 2-2, determines the global average vertical distribution of temperature. If the concentration of certain trace gases (carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), and chlorofluorocarbons (CFCs)) increases, the atmosphere's absorption of longwave radiation (thermal radiation from the Earth's surface) will increase. Some of this energy will be radiated downward, heating the surface and increasing the surface temperature. Because the concentrations of all these gases are projected to increase in the future, this effect and its timing must be compared to the other projected causes of climate change (forcings), and the response of the climate system, to project the future climate. Uncertainties are associated with all these factors.

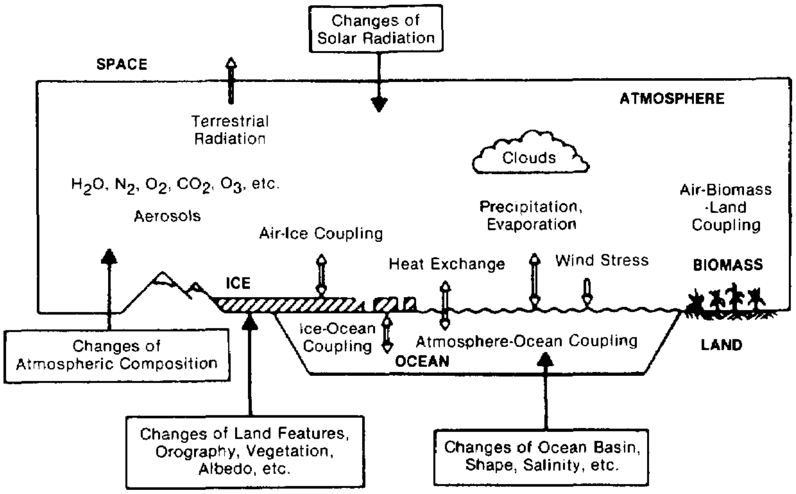

Figure 2-1. The climate system. The principal interactions among components of the atmosphere, ocean, ice, and land surface, and some examples of external forcings are indicated (Gates, 1979).

Climate Terminology

Although this report avoids most technical jargon, some specialized terminology is inevitable. These terms are defined below.

aerosols	Tiny solid or liquid particles suspended in the atmosphere. Volcanic dust, forest fire smoke, and cloud droplets are examples.
albedo	Fraction of incoming solar radiation that is reflected. The fraction of energy absorbed is equal to 1 minus albedo. Thus, if the albedo of the earth's surface goes down, e.g, by snow melting that uncovers darker land, then the amount of energy absorbed would go up, raising the temperature.
energy	[also called heat balance] The process by which climate is determined. At any point balance on Earth, the incoming solar energy is balanced by outgoing thermal radiation, storage or release of heat in the surface, and redistribution of heat by wind and ocean currents.
longwave	[also called infrared radiation or thermal radiation] Electromagnetic radiation, like radiation light (solar radiation), radio waves and x-rays (microwaves), but of the wavelength that every object emits in order to cool itself. The Earth's surface emits longwave radiation in the wavelength region that is absorbed by CO_2, $H_2$0, and other greenhouse gases, producing the greenhouse effect, since these gases are much more transparent to sunlight.
ppmv, ppbv	Parts per million by volume, parts per billion by volume; units of concentration of gases. The 1989 concentration of CO_2 in the atmosphere is about 0.035% = 350 ppmv = 350,000 ppbv. The 1989 concentration of CFC-11 is about 0.000000026% = 0.00026 ppmv = 0.26 ppbv.
sink	Mechanism that removes a gas from the atmosphere. For example, oceans serve as a sink for CO_2, which dissolves in the surface waters.
source	Mechanism that adds a gas to the atmosphere. For example, foam blowing, leaky automobile air conditioners, and cleaning computer chips are all sources of CFCs.
stratosphere	The atmospheric layer above the troposphere, extending from the tropopause (the top of the troposphere) to about 50 kilometers (31 miles). The troposphere and stratosphere together contain more than 99.9% of the mass of the atmosphere.
thermal	Resistance to temperature change. Oceans have a much larger thermal inertia than inertia land because heat added or subtracted must come or go from a thick layer of well-mixed water rather than a thin immobile layer of soil.
trace gas	A gas with a very low concentration in the atmosphere. The important greenhouse trace gases are discussed in this chapter in the section on climate forcings.
troposphere	The lowest atmospheric layer, which extends from the Earth's surface to a height of about 8 kilometers (5 miles) in the polar regions, 12 kilometers (7 miles) in the midlatitudes, and 18 kilometers (11 miles) in the tropical regions. All weather and precipitation take place in the troposphere, which contains about 80% of the mass of the atmosphere.

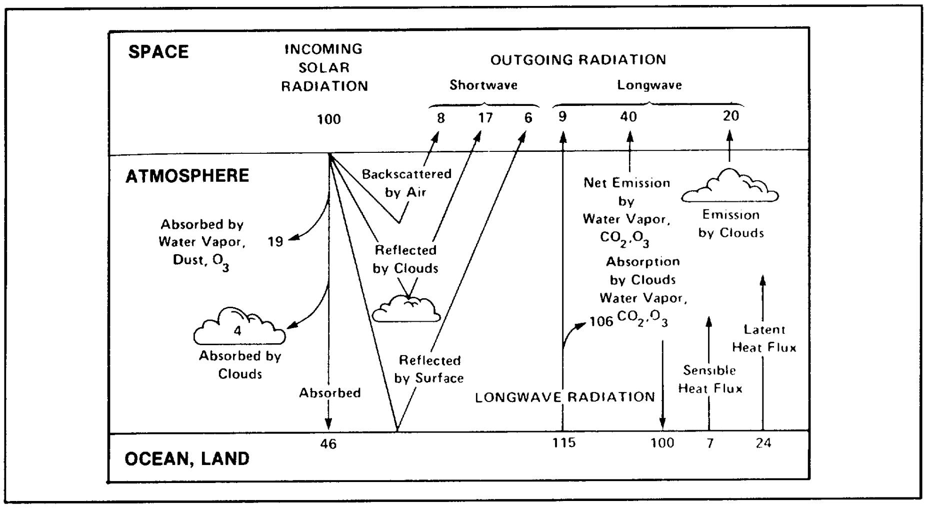

Figure 2-2. The Earth's energy balance. If the average amount of solar radiation received by the Earth (342 watts per meter2) is represented as 100 units, then the amplitudes of the various components of the energy flux are shown proportionately (MacCracken, 1985).

CLIMATE FORCINGS

Both the past and future courses of climate change are determined by a combination of external forcings, unforced internal fluctuations, and the response of the climate system. This section briefly discusses the forcings that will be important in the next century.

Greenhouse Gases

If the Earth had no atmosphere, its average surface temperature, determined by the balance between incoming solar radiation and emitted longwave radiation at the surface, would be about 0°F (-18°C), the same as the current temperature of the moon. The average temperature is actually a hospitable 59°F (15°C) because of the natural greenhouse effect of H_2O, CO_2, and O_3. Because a large amount of the radiation in the wavelength band 7 to 13 micrometers is not absorbed by these gases, it is referred to as the "atmospheric window," and is a region where longwave radiation can escape relatively unimpeded to space.

The concentration of a number of trace gases in the atmosphere is increasing as a result of human activities. Because the trace gases are very effective absorbers of longwave radiation in the atmospheric window region, small (trace) amounts can have large effects on the radiation balance, in effect "dirtying" the atmospheric window. Trends and concentrations of some of these gases are shown in Table 2-1 and Figure 2-3. The projected relative effects of these gases are shown in Figure 2-4. Each of the gases is discussed in more detail below.

Carbon Dioxide (CO_2)

Combustion of fossil fuels and deforestation are increasing the concentration of CO_2. Since Keeling began detailed measurements during the International Geophysical Year in 1958 at Mauna Loa, Hawaii, the atmospheric concentration of CO_2 has risen from 315 ppmv (0.0315%) to a current level of 350 ppmv. About half of the CO_2 put into the atmosphere each year remains in the atmosphere, with the rest absorbed in the ocean. Because society's basic energy sources (combustion of coal, oil, and natural gas) produce CO_2, unless strong energy conservation measures and shifts to other energy sources take place, it is projected that the atmospheric concentration of CO_2 will continue to increase. As climate changes, the effectiveness of the oceanic sink for CO_2 may also change, increasing or decreasing the fraction of CO_2 that remains in the atmosphere. CO_2 contributes about half of the total anthropogenic greenhouse forcing.

Methane (CH_4)

Although the methane concentration is now increasing at a rate of about 1% per year and was much lower during the ice ages, the basic cycle is not

Table 2-1. Trace Gas Concentrations and Trends

Gas	Concentrations		Current annual observed trends (%)	Mid-21st century
	Pre-1850	1987		
CO_2	275.00ppmv[a]	348.00ppmv	0.3	400.00-550.00ppmv
CH_4	0.70ppmv	1.70ppmv	0.8-1.0	1.80-3.20ppmv
N_2O	0.29ppmv	0.34ppmv	0.2	0.35-0.40ppmv
CFC-11	0	0.22ppmv[b]	4.0	0.20-0.60ppbv
CFC-12	0	0.39ppmv[b]	4.0	0.50-1.10ppbv
CH_3CCl_3	0	0.13ppmv[b]	7.0	
CCl_4	0	0.08-0.10ppmv[b]		
O_3	0	10.00-100.00ppmv[d]		

[a] Units of ppmv are parts per billion by volume; 1 ppmv = 0.0001% of the atmosphere. Units of ppbv are parts per billion by volume; 1 ppbv = 0.001 ppmv.

[b] Value given is for 1986.

[c] Trapospheric ozone only (below 12 kilometers). Values (below 9 km) for before 1850 are 0 to 25% less than present-day; values (12 kilometers) for mid-21st century are 15 to 50% higher.

[d] Value given is for 1985.

Source: Ramanathan (1988), Lashof and Tirpak (draft 1989).

completely understood. Sources include rice paddies, cows, termites, natural gas leakage, biomass burning, landfills, and wetlands. Although methane has a much lower atmospheric concentration than CO_2 (currently 1.7 ppmv), it is more effective at dirty CCl4 ing the atmospheric window and accounts for about 18% of current anthropogenic greenhouse forcing.

Chlorofluorocarbons (CFCs)

These completely anthropogenic gases, the most important of which are known by the trade name Freon, have been implicated not only in greenhouse warming but also in chemical destruction of stratospheric ozone (03). Because of this, nations agreed to limit production of these gases in an international agreement signed in Montreal in 1987. The most important of these gases are CFC-11 ($CFCl_3$) and CFC-12 (CF_2C1_2). CFCs are used in refrigerants, aerosol propellants, foam-blowing agents, and solvents. Substitutes for CFCs are being developed that are not as stable chemically and, therefore, would not accumulate as fast in the atmosphere. The resulting lower concentration would produce a smaller greenhouse effect and would be less effective at destroying O_3. The current fractional greenhouse contribution of CFC-11 and CFC-12 of 14% would probably decrease in the future, but the total CFC greenhouse effect would most likely increase for some time because of the long lifetime of these gases.

Nitrous Oxide (N_2O)

This gas, with both natural and anthropogenic sources, contributes about 6% to the enhanced greenhouse effect, although its concentration is only about 0.31 ppmv. Its concentration is increasing at a rate of about 1 ppbv per year, and sources include oceans, fossil fuel and biomass combustion, agricultural fertilizers, and land disturbances.

Ozone (O_3)

In addition to its role in the stratosphere as an absorber of ultraviolet shortwave radiation, O_3 has an important impact on climate. This role is complicated by its dependence on the altitude where O_3 occurs. Both ozone increases in the troposphere and lower stratosphere and ozone decreases in the upper stratosphere would tend to warm the surface.

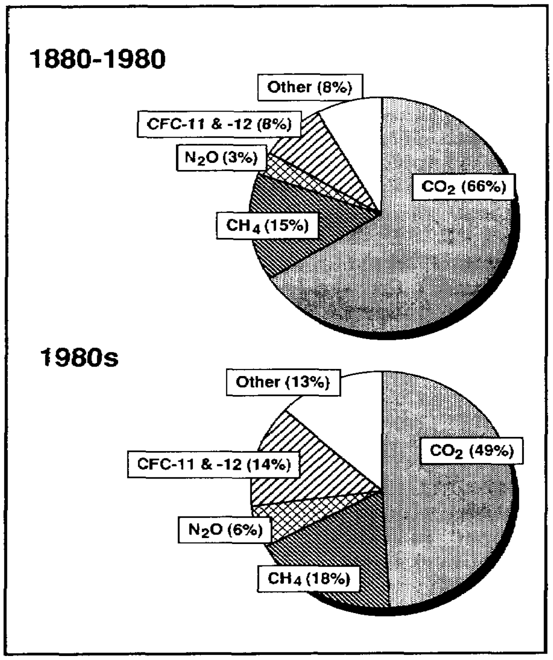

Figure 2-4. Greenhouse gas contributions to global warming; estimated values based on concentration changes (1880-1980: Ramanathan et al., 1985; 1985, 1980s: Hansen et al., 1988).

Although the ozone concentration is believed to be increasing in the troposphere, it is active chemically and has highly variable concentrations in time and space. Responding to local air pollutants, such as nitrogen oxides (NO_x)and hydrocarbons, ozone provides a complex link between local air pollution and global climate change. Other gases, such as carbon monoxide (CO) and volatile organic compounds, also play important roles in atmospheric chemistry and hence affect the greenhouse problem.

Solar Variations

The sun provides the energy source for all weather on the Earth, and the balance between incoming sunlight and outgoing longwave radiation determines the climate. Small variations in solar radiation have the potential for causing climate changes as large as those caused by projected increases of greenhouse gases. Precise observations of the sun have been taken only for the past decade (Willson and Hudson, 1988). They show, however, that solar variations during this period have been so small that they would not be important compared with the other forcings discussed in this section. Since these high-quality observations have been taken only for a short period, they do not rule out past or future variations of the sun that would be larger. But on the time scale of centuries, solar variations do not now seem to be an important factor.

Volcanoes

Large volcanoes can significantly increase the concentration of stratospheric aerosols, decreasing the amount of sunlight reaching the surface and reducing surface temperatures by several tenths of degrees for several years (Hansen et al., 1978, 1988; Robock, 1978, 1979, 1981, 1984). Because of the thermal inertia of the climate system (discussed below), volcanoes can even be responsible for climate changes over decades. It has been suggested that a significant part of the observed global climate change of the past 100 years can be attributed to the effects of volcanic eruptions (Robock, 1979). Since large eruptions occur fairly frequently, this component of climate change will have to be considered when searching past climate for a greenhouse signal and when projecting future climate change.

Tropospheric Aerosols

Natural sources, such as forest fires and sea spray, and human activities generate atmospheric aerosols in the troposphere. The concentrations vary greatly in space and time, and local sources are important. Furthermore, these aerosols can produce either warming or cooling, depending on their concentration, color, size, and vertical distribution. It is not now possible to definitively determine their role in global climate.

Surface Properties

The Earth's radiative balance can also be changed by variations of surface properties. While interactions with the oceans which cover 70% of the Earth's surface, are considered internal to the climate system, land surfaces can exert a strong influence on the climate. Human activities, such as deforestation, not only provide a source of CO_2 and CH_4 to the atmosphere but also change the surface albedo and rate of evaporation of moisture into the atmosphere. Detailed land surface models, incorporating the effects of plants, are now being developed and incorporated into climate model studies (Dickinson, 1984; Sellers et al., 1986).

Internal Variations

Even with no changes in the external forcings discussed above, climate exhibits variations due to internal rearrangements of energy both within the atmosphere and between the atmosphere and the ocean. The total amplitude and time scales of these variations are not well understood; this contributes to the difficulty of interpreting the past record and projecting the level of future climate change.

Some studies suggest that these random variations can have amplitudes and time scales comparable to climate changes expected to be caused by greenhouse warming in the coming decades (Lorenz, 1968; Hasselmalm,1976; Robock, 1978; Hansen et al., 1988). A large El Nino, such as that observed in 1982-83, can take large amounts of energy out of the oceans and warm the surface climate for a few years; this warming is then superimposed on any warming due to the greenhouse effect. Our understanding of these El Niño/Southern Oscillation variations is improving, allowing us to account for this factor in interpreting past global climate change (Angell, 1988).

CLIMATE FEEDBACKS

Any imposed imbalance in the Earth's radiative balance, such as discussed above, will be translated into a changed climate through feedback mechanisms that can amplify or decrease the initial imposed forcing. A feedback in which the final temperature is higher than what it would have been without the feedback is termed a "positive feedback." If the effect of the initially imposed forcing is reduced, it is termed a "negative feedback." This section describes several of these mechanisms that are internal to the physical climate system and that involve the planet's biology and chemistry.

Although important climate feedback mechanisms have been identified, we may not understand or even know about all the mechanisms involved in climate feedbacks. Figure 2-5 shows that even with the known physical climate feedbacks involved in changing surface temperature, the potential interactions are complex. Current state-of-the-art climate models attempt to incorporate most of the physical feedbacks that have been identified but are forced, for example, to provide a very crude treatment for one of the most important -- ocean circulation -- because of large computer demands and inadequate ocean climate models. Another important and inadequately understood feedback -- clouds -- has been the subject of recent climate calculations but, as described below, is also treated crudely owing to inadequate understanding of cloud physics and the small spatial scale on which clouds form as compared with the resolution of the climate models.

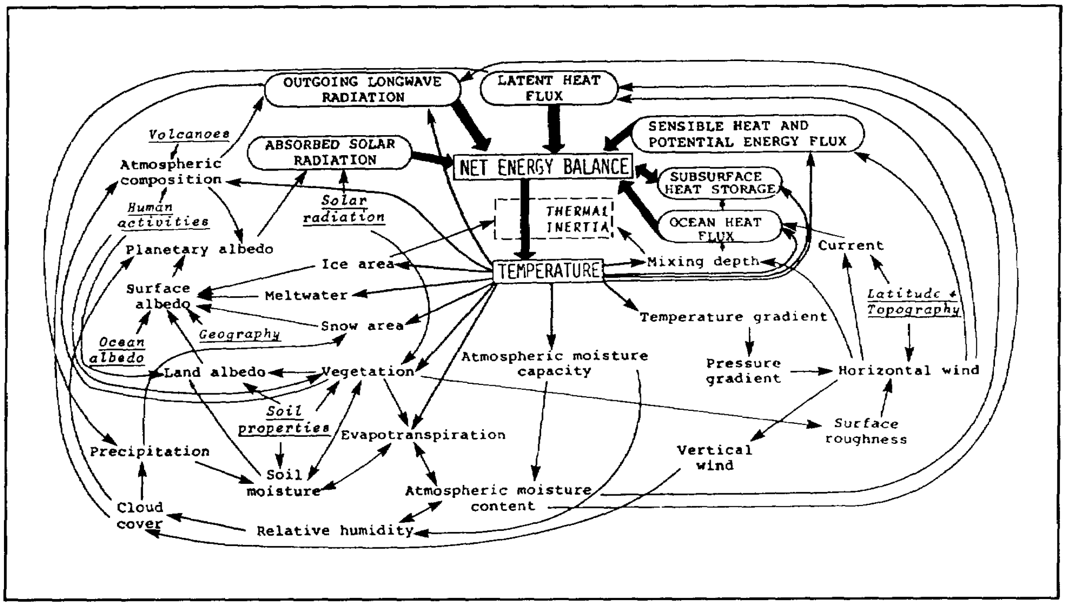

Figure 2-5. Physical climate feedback relationships. External forcings are indicated in underlined italics (Robock, 1985).

Water Vapor -- Greenhouse Effect

When the climate warms, more water (H_2O) evaporates into the atmosphere from the warmed surface. This enhances the warming because it increases the greenhouse effect of the water vapor, producing still more evaporation. This positive feedback acts to approximately double imposed forcings. Thus, an important greenhouse gas, H_2O vapor, is controlled by the climate system itself. Transformations of H_2O between vapor and other phases, liquid and solid, provide other important climate feedbacks discussed below.

Snow and Ice

When climate warms, snow and ice cover are reduced, exposing land or ocean with a lower albedo than the snow or ice. In addition, the albedo of the remaining snow and ice is reduced owing to meltwater puddles and debris on the surface. This acts to absorb more energy at the surface, further enhancing the warming. This albedo feedback was originally thought to be the dominant positive feedback effect of snow and ice, but we now understand that the thermal inertia feedback of sea ice plays a much more important role (Manabe and Stouffer, 1980; Robock, 1983).

The thermal inertia feedback acts to increase the thermal inertia of the oceans when climate warms by melting sea ice and exposing ocean waters to the atmosphere. Since imposed climate change must then affect the ocean and atmosphere together rather than the atmosphere alone, this acts to reduce the seasonal cycle of surface temperature and is the prime reason for the enhancement of imposed climate change in the polar regions in the winter (Robock, 1983).

Clouds

Clouds respond directly and immediately to changes in climate and may represent the most important uncertainty in determining the sensitivity of the climate system to the buildup of greenhouse gases. Fractional cover, altitude, and optical depth of clouds can change when climate changes (Schlesinger, 1985). At the present time, clouds have a large greenhouse effect, but this is offset (averaged over the globe) by their even stronger cooling effect, because clouds reflect sunlight back to space (Ramanathan et al., 1989). Since the current greenhouse effect of clouds is larger than the effect of an increase of CO_2 by a factor of 100, small changes in clouds as climate changes can be very important in affecting the overall climate response to increases in trace gases.

If climate becomes warmer, more water will evaporate into the atmosphere. Coupled with warmer surface temperatures, this may produce more upward motion of air, which would produce more clouds. One way clouds could increase is to increase in area. This would raise the albedo of the planet (except over polar snow and ice fields, which have an albedo larger than clouds), reflecting more sunlight back to space and having a cooling effect. Thus, the initially imposed warming is reduced, producing a negative feedback. Clouds already increase the planetary albedo from about 17% (if there were no clouds) to 30% (Ramanathan et al., 1989). An increase of planetary albedo of only 0.5% would cut in half the warming imposed by doubled CO_2 (Ramanathan, 1988).

Other studies suggest that, especially in the tropical regions, convection could increase, producing taller but narrower clouds. This would produce additional warming in two ways: (1) by reducing the cloud area, thus decreasing the planetary albedo; and (2) by decreasing the cloud top temperature and reducing longwave radiation to space. This mechanism would be a positive feedback. In addition, convective clouds in the tropical regions (thunderstorms) tend to produce large shields of high cirrus clouds, which have a large greenhouse effect further enhancing the warming. Cirrus clouds allow much sunlight to penetrate because they are so thin, but the cloud particles absorb the outgoing longwave radiation from the surface, efficiently trapping much of it (Ramanathan, 1988).

In the latest climate model simulations, it was found that clouds have a net positive feedback on global climate (Schlesinger, 1988), but the final answer will be known only after more research. It is not possible to be certain of the net effect of cloud feedbacks because of the complexity of clouds and their response to climate change. The complexity is because all the above properties of clouds can change simultaneously, because clouds affect both longwave and shortwave radiation, because clouds affect precipitation (which affects land temperatures), and because the net effect depends on the location of the cloud, surface albedo, time of day, and time of year.

Biogeochemical Feedbacks

In addition to the physical climate feedbacks discussed above, a number of positive biogeochemical feedbacks may be important (Lashof, 1989). These feedbacks can influence future concentrations of greenhouse gases, especially CO_2 and CH_4, through changes in sources and sinks of these gases induced by climate change, and they can influence the climate change itself through changes in vegetation, and hence the surface heat and moisture balance. Such processes include changes in releases of methane hydrates from ocean sediments, changes of land albedo due to shifting ecosystems, and changes in the ability of the oceans to absorb CO_2 (this process is discussed in the next section).

Methane hydrates are combinations of a methane molecule trapped in a lattice of water molecules. They are found in ocean sediments and are stable under current pressure and temperature conditions in many ocean shelf regions. As the climate warms, these conditions may change, releasing more methane into the atmosphere and enhancing the greenhouse effect.

As the climate warms, forests may shift closer to the pole, producing a region with a lower albedo. The surface will thus absorb a larger fraction of sunlight, warming the Earth and producing a positive feedback, further enhancing the warming.

Oceans

Oceans play an important role in the climatic response to changed forcings because they absorb and emit both heat and CO_2 and because changing ocean circulation can change the redistribution of energy internal to the climate system, as discussed above. When any of the above climate forcings are applied to the climate system, the climate will start to change. Since both the climate forcings and the climatic response are time-dependent, and since the climate system has a certain amount of inertia built in owing to the response times of the ocean, the exact relationship between the timing of the forcings and the timing of the response is complex. Much of the lag between the imposed forcing and the climatic response depends on the oceans. The upper 50 to 100 meters (164 to 328 feet) of the ocean, called the mixed layer, responds relatively rapidly to imposed forcings. The deep ocean is also important because its interactions could impose lags of as much as 100 years.

The relative depth and role of the mixed layer, as well as the circulation of the ocean, will change in a complex way in response to changed climate. Broecker (1987) has suggested that a rapid shift in ocean currents, such as the Gulf Stream, may occur as the climate warms, producing large regional and relatively rapid global climate changes. In preliminary tests with the Geophysical Fluid Dynamics Laboratory models, when CO_2 is doubled, the oceanic circulation around Antarctica changes so as to increase the upwelling of cold bottom water. As a result, cooling occurs in the Southern Hemisphere high latitudes for a period of several decades as the rest of the globe warms! These two examples suggest that unforeseen climate events may be possible in the future and that until the ocean response is well understood, the timing and amplitude of the climatic response to increased greenhouse gases and the other forcings will need to remain the subject of additional research.

Oceans are also the dominant sink of atmospheric CO_2, absorbing about half of all CO_2 that is put into the atmosphere each year by the combustion of fossil fuels and deforestation. The amount of absorption is a strong function of oceanic temperature, and shifts in oceanic circulation and temperature may shift the fraction of CO_2 absorbed in the future and, hence, change the rate of CO_2 accumulation in the atmosphere. As the oceans warm, they may absorb a smaller fraction of the excess CO_2 in the atmosphere, thereby enhancing the warming (Lashof, 1989). In addition, oceanic chemical reactions change as climate changes. Oceanic production of dimethyl sulfide particles could also change as climate changes (Charlson et al., 1987). These particles serve as cloud condensation nuclei and may change the reflectivity of marine clouds by changing the number of droplets in the clouds.

Observational Evidence of Climate Change

Thermometers have been used to actually measure global climate change for more than 100 years in enough locations to provide an estimate of how the planet's climate has changed during this period. The most complete and up-to-date global surface air temperature record available is shown in Figure 2-6 (Wigley et al., 1989). Other analyses, including Hansen and Lebedeff (1988) and Vinnikov et al. (1987), give similar results. Problems common to all these data sets

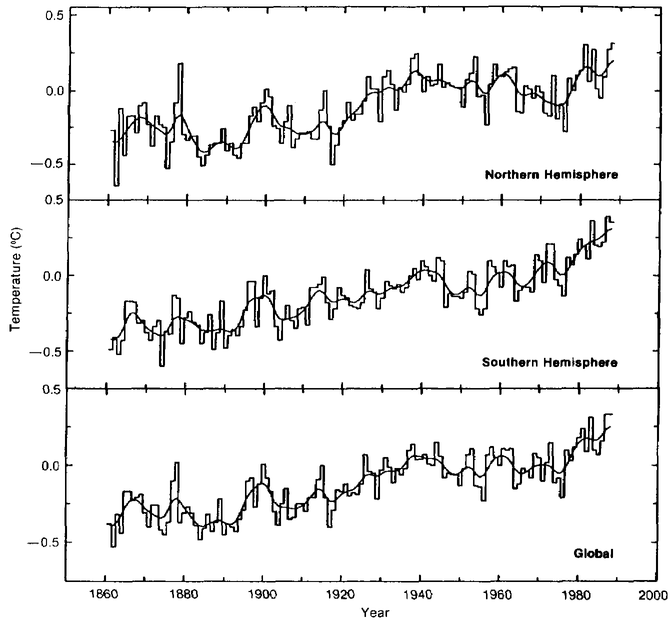

Figure 2-6. Hemispheric and global surface air temperatures, 1861-1988. The 1988 value is preliminary and includes data only through November. This record incorporates measurements made both over land and from ships. The smooth curve shows 10-year Gaussian filtered values. The gradual warming during this period is not inconsistent with the increasing greenhouse gases during this period, but the large interannual variations and the relatively flat curve from 1940 to 1975 show that there are also other important causes of climate change (Wigley et al., 1989).

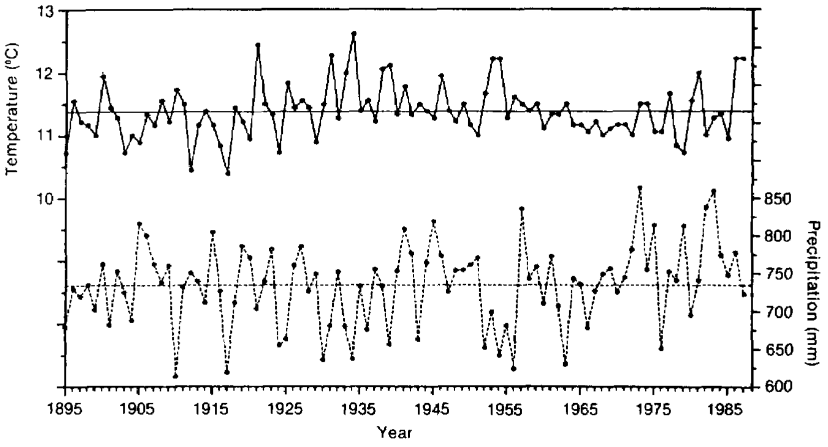

Figure 2-7. Annual average surface air temperature (solid) and precipitation for the contiguous United States, 1895-1987. Note that the United States has been cooling for the past 50 years (Hansen et al., 1988).

include possible contamination from urban heat islands, inadequate spatial coverage of the Earth, and corrections necessary to counteract the effects of changing the methods used to take observations from ships.

While the gradual warming seen in Figure 2-6 during the past century is consistent with the increasing greenhouse gases during this period, most scientists suggest that a clear link has not yet been established between observed temperatures and the greenhouse effect. The large interannual variations and the relatively flat curve from 1940 to 1975 show that there are also other important causes of climate change. For example, large volcanic eruptions, such as Hekla in 1947 and Agung in 1963, and El Niños certainly have produced some of the variations shown in this record. Because of the projected future emissions of greenhouse gases, global warming is likely to dominate these factors during the next century.

The global temperature record shown in Figure 2-6 can also be compared with the record for the United States for the same period shown in Figure 2-7 (Hanson et al., 1989). While the globe as a whole has been generally warming, the lower 48 states of the United States have actually been cooling for the past 40 to 50 years, although the high temperatures in the 1980s are among the warmest on record. Since the lower 48 states of the United States cover only 1.5% of the planet, this indicates that regional climatic variations, which may be caused by changes in sea surface temperature and wind circulation patterns, can be an important factor in the climate of small regions of the Earth. These factors will continue to be important as global climate warms. For example, such regional events as the midwestern drought of 1988 may be related to changes in ocean temperature (Trenberth et al., 1988) and can be greater than the effect of greenhouse gases on a national or larger scale.

On a longer time scale, proxy climate variables can indicate how climate has changed. An intriguing record comes from a core drilled in the antarctic icecap at Vostok and is shown in Figure 2-8 (Barnola et al., 1987). The temperature record is deduced from the deuterium isotope ratio. The past CO_2 concentration is actually measured from bubbles of ancient air trapped in the ice. The warm period of the past 10,000 years is called the Interglacial and represents an anomalously warm period compared with the climate of the past 100,000 years. It is projected that because of the greenhouse effect, our climate will warm to a level much above even the level of the Interglacial, warmer in fact than the Earth has experienced for the past million years. The rate of warming will also be unprecedented. From Figure 2-8, it appears that the warming from the chill of the ice age 18,000 years ago to the Interglacial was very rapid, but in fact a warming of even 2°C in one century would be much faster than this warming.

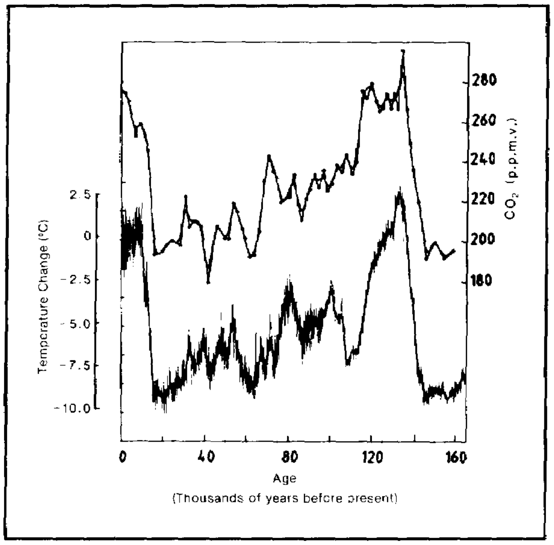

Figure 2-8. Temperatures and carbon dioxide concentrations for the past 160,000 years at Vostok, Antarctica. Since these observations were taken near the South Pole, they show larger temperature variations (by a factor of 2 or 3) than took place averaged over the whole globe (Barnola et al., 1987).

Figure 2-8 shows that during the entire 160,000-year period, the atmospheric CO_2 concentration varied along with the temperature. When it was warmer, the CO_2 concentration was higher, although it never approached the current level of 350 ppmv. It is not known whether the climate change preceded the increase in CO_2, whether the increase in CO_2 preceded the warming, or whether they both happened simultaneously. It is well accepted that the changing orbit of the Earth produced the ice ages (the Milankovitch Hypothesis), and this recently discovered variation of CO_2 certainly worked to enhance the climate changes caused by the changing orbit. These natural processes are now being overwhelmed by the human impact of fossil fuel burning and deforestation.

Two recent studies of CH_4 concentration in ancient air found in Greenland and Antarctic ice cores also have shown that CH_4 concentration varied with climate in prehistoric times (Stauffer et al., 1988; Raynaud et al., 1988). Although the CH_4 concentrations were not large enough to have an appreciable impact on the greenhouse effect, the CH_4 did vary in the same sense as CO_2. and climate (see Figure 2-8). The CH_4 variations indicate that sources of CH_4 increase in a warmer climate, which suggests that natural sources of CH, may also increase in the future as global climate warms, further amplifying the greenhouse effect.

CLIMATE MODELS

In many sciences, such as biology, chemistry, or physics, it is possible to investigate new phenomena by doing research in a laboratory. In the field of climate, this is not possible. One cannot bring the Earth's climate system into a room and perform experiments on it, changing the trace gas concentration or increasing the amount of sea ice. It is not possible to have two identical systems, one a control and one that is changed to compare the outcomes. There is only one climate system, and humans are now performing an uncontrolled experiment on it by polluting it with CO_2, CH_4, CFCs, and other trace gases.

To try to understand how the global climate will change in response to human activities, researchers have applied various approaches. The climates of other planets, particularly Venus and Mars which are the most Earth-like, can give us some ideas about climate under very different conditions. However, their atmospheres are not similar enough to Earth's to give us definitive answers about the next 100 years here. The history of the Earth's climate is another area we could study, but since many different forcings of similar strengths have been acting, and since the data coverage is imperfect, it has not been possible to definitively isolate the roles of the different forcings. Attempts have been made to use rotating tanks of water or other fluids (called dishpan experiments) as models for the atmosphere, but these are imperfect as they cannot simulate realistic heating profiles or the detail of the real climate system.

The most useful tool to investigate future climate is the computer model of the climate system. In a climate model, the various physical laws that determine the climate, such as conservation of energy, conservation of mass, and the gas law, are expressed as mathematical equations that specify the relationship between different variables, such as temperature, pressure, wind, and precipitation. By specifying the various climate forcings, it is possible to calculate the climate. An experiment can be performed by doubling CO_2, for instance, and comparing the resulting climate to the current CO_2 concentration. Many theoretical calculations can lie made to test the importance of various assumptions and various proposed feedback mechanisms.

The simplest climate model is the zero-dimensional global average model, which can be used to give a global-average measure of climate but cannot consider many important processes and cannot give regional distribution of climate changes. Models that are one-dimensional in the vertical, called radiative-convective models, or in the horizontal, called energy-balance models, are very useful for quickly and inexpensively testing various components of the climate system. However, to calculate the location of future climate change, and to incorporate all the important physical interactions, especially with atmospheric circulation, fully three-dimensional general circulation models (GCMs) are necessary. These sophisticated models solve simultaneous equations for all the important climate variables in three dimensions. The world is broken up into a discrete grid of boxes placed side by side and stacked to cover the globe. The biggest and fastest supercomputers available are used, but computer speed and size constraints limit the size of these grid boxes to 250 to 1,000 kilometers (150 to 600 miles) on a side and to a height of 1 to 5 kilometers (0.6 to 3 miles). Thus, in one of these grid boxes, all the complexity of weather and horizontal variation is reduced to one number for temperature, one for cloudiness, and so forth. The equations used to represent the physical and chemical processes involved are also simplifications of real-world processes.

Different climate modelers represent physical processes in different ways. In all the models, the radiation schemes attempt to account for the radiatively significant gases, aerosols, and clouds.

They generally use different schemes for computing cloud height, cloud cover, and optical properties. The models also differ in their treatment of ground hydrology, sea ice, surface albedo, and diurnal and seasonal cycles (Schlesinger and Mitchell, 1985). Perhaps the most important differences lie in the treatment of oceans, ranging from prescribed sea surface temperatures to "swamp" oceans with mixed-layer thermal capacity but no heat transport, to mixed layers with specified heat transport, to full oceanic GCMs. Models are constantly becoming more complex and sophisticated as new understanding of the physics evolves and faster computers become available.

One of the first experiments used to test any climate model is its ability to simulate the current climate. In these tests, the various state-of-the-art climate models have differences. Grotch (1988) has recently compared the simulations of surface air temperature and precipitation of four recent GCM simulations and found that although they do a reasonable job of simulating global values, the simulations at the regional scale are poor. He compared model simulations and observations on gridpoints, where each gridpoint "represents a region of about 400 kilometers (250 miles) by 400 kilometers or larger, or roughly the size of Colorado, even though regions of this size may have very diverse local climates" (Grotcl4 1988). He found differences between models and observations (see Table 2-2), and between models, particularly for smaller regions. Grotch concluded that GCMs cannot currently project regional changes of precipitation or temperature.

Given the current state of the art, how can these models be used? As discussed in Chapter 4, model simulations can be of use even in their crude state. In the first place, even if the models do not exactly reproduce the current climate, perhaps the differences between their simulations of current and future climates provide an estimate of potential future changes. In addition, the models produce a data set of all the variables needed for impact assessment that are physically consistent within the physics of the model. Thus, although the actual model projections can not be taken as predictions of the future, they are useful in providing scenarios for impact assessment. As model projections become more accurate in the future, the scenarios they generate will become more accurate.

In generating scenarios, an important component is the timing of future climate changes. This depends not only on the timing of the changes in the forcing (how rapidly trace gas concentrations increase) but on the sensitivity of the climate system to these forcings. A simpler question to ask is, "What would be the change in global average surface air temperature if the CO_2 concentration in the atmosphere were doubled from the preindustrial level, all other climate forcings were held constant, and the climate became completely adjusted to the new radiative forcing?" This is referred to as the equilibrium climate sensitivity to a CO_2 doubling. When discussing climate change, it is sometimes convenient to refer to an "equivalent doubling of CO_2," which means the effect of all the greenhouse gases together that would have the same effect as doubling CO_2. This would occur with less than a doubling of CO_2 itself, since the other anthropogenic greenhouse gases currently contribute approximately the same amount of warming as does CO_2. While it is reasonable to lump all the greenhouse gases together for the purposes of calculating the radiative effect, the other effects of these gases, such as fertilization of plants by CO_2 or chemical reactions, must be determined based on the actual concentrations of each gas.

Model Projections of a Doubled-CO_2 World

Several climate modeling groups have conducted GCM experiments to calculate the equilibrium climate response to doubled CO_2. These include researchers at the National Center for Atmospheric Research (NCAR), Oregon State University (OSU), NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), NASA's Goddard Institute for Space Studies (GISS), and the United Kingdom Meteorological Office (UKMO). The results from the different experiments depend on the assumptions made, especially on the treatment of clouds and of oceans. The models predicted global temperature increases of 2.8 to 5.2°C and global precipitation increases of 7 to 16% (see Table 2-3).

Table 2.2 Differences Between Winter and Summer Temperature Estimates for Four GCMs and Observed Temperatures

Variable and Model	Global	Domain of Comparison		
		North America	Contiguous U.S.	Midwestern U.S.
December - January - February				
Observed median temperature (°C)	8.5	-5.8	0.9	-1.5
Differences in median temperatures (CGM - Observation)				
CCM	-1.6	-0.3	-2.1	-0.5
GFDL	1.5	-1.8	-0.8	-1.3
GISS	0.8	-0.5	0.0	1.1
OSU	0.3	0.5	-0.6	-1.0
June - July - August				
Observed median temperature (°C)	13.9	18.9	23.0	23.0
Differences in median temperatures (CGM - Observation)				
CCM	1.3	6.0	6.3	6.8
GFDL	-0.2	0.6	0.1	3.7
GISS	0.4	-3.1	-4.5	-4.8
OSU	-0.6	-2.2	-2.2	-1.6

CCM = Community Climate Model (National Center for Atmospheric Research). This is the Washington version discussed in Chapter 3: Variability.
Source: Grotch (1988).

Table 2-3. General Circulation Model Predictions of Globally Averaged Climate Change Due to Doubled CO_2

Model	Surface air temperature increase (◦C)	Precipitation increase (%)
GFDL	4.0	8.7
GISS	4.2	11.0
NCAR	3.5	7.1
OSU	2.8	7.8
UKMO	5.2	15.8

Source: Karl et al. (1989).

Attempts have also been made to determine climate sensitivity from past data. If we could accurately determine the strength and timing of all the climate forcings that have competed with the greenhouse effect in the past, we could account for them, and the residual warming would be a measure of the greenhouse effect to date. Unfortunately, our knowledge of both past climate change and the responsible forcings is too poor to reliably determine the sensitivity of climate to greenhouse warming. Wigley and Raper (1987) estimate that if all of the warming of the past 100 years were due to greenhouse gases, a doubling of CO_2 would warm climate by about 2°C. If, however, we allow for other possible forcings (including natural variability), for uncertainties in ocean heat uptake and the timing of the climate response, and for uncertainties in preindustrial greenhouse gas concentrations (Hansen et al., 1985; Wigley and Schlesinger, 1985; Wigley et al., 1986), then from past data we can only say that a CO_2 doubling might produce a global climate change anywhere in the range of 0 to 6°C (Wigley, personal communication). Wigley et al. (1989) point out that while the global warming of the past 137 years is highly significant statistically, it is not possible to definitively attribute this warming to a specific cause.

The actual path that the climate system would take to approach the equilibrium climate would be determined by the time scales of the forcings and the various elements of the climate system and is referred to as the transient response. Because the climate system response lags behind the forcing, a built-in unrealized warming will always occur in the future, even if no more greenhouse gases are added. Thus, some future climate response to the greenhouse gases that were put into the atmosphere in the past will certainly occur, even if emissions were stopped today.

What We Know About Future Climate

A panel of experts convened by the National Academy of Sciences (National Research Council, 1987) recently considered the climatic response to increasing greenhouse gases and gave the following assessment, including their estimate of scientific confidence in the predictions. This table is limited to a summary of their conclusions :about °the possible climate response to increased greenhouse gases" only; the full report should be consulted for the details:

Large Stratospheric Cooling (virtually certain). The combination of: increased cooling by additional CO_2 and other trace gases, and reduced heating by reduced 03, “will lead to a major lowering of temperature in the upper stratosphere.”

Global-Mean Surface Warming (very probable). For an equivalent doubling of CO_2, “the long-term global-mean surface warming is expected to be in the range of 1.5 to 4.5°C.”

Global-Mean Precipitation Increase (very probable). “Increased heating of the surface will lead to increased evaporation and, therefore, to greater global mean precipitation. Despite this increase in global average precipitation, some individual regions might well experience decreases in rainfall.”

Reduction of Sea Ice (very probable). This will be due to melting as the climate warms.

Polar Winter Surface Warming (very probable). As a result of sea ice reduction. polar surface air may warm by as much as three times the global average.

Summer Continental Dryness/Warming (likely in the long term). Found in several but not all studies, it is mainly caused by earlier termination of winter storminess. “Of course, these simulations of long-term equilibrium conditions may not offer a reliable guide to trends over the next few decades of changing atmospheric composition and changing climate.”

Rise in Global Mean Sea Level (probable). This will lie because of thermal expansion of seawater and melting or calving of land ice.

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CHAPTER 3
VARIABILITY

by Linda O. Mearns

FINDINGS

A changed climate variability (defined in the following section of this chapter) associated with climate change could significantly affect natural resources. However, lack of information on potential changes in climate variability has limited the completeness of climate change impact studies presented in this report. It is not possible to definitively state how climate variability will change with a changed climate because model results are mixed. At this time, there is not a strong case for altering the assumption of no change in variability used in the scenarios for this report.

Analyses of changes in climate variability for a CO_2 doubling estimated by two general circulation models (GCMs) -- Goddard Institute for Space Studies (GISS) and National Center for Atmospheric Research (NCAR) -- are not conclusive. Some overall trends, but also some inconsistencies, are obtained when comparing the changes in climate variability associated with a changing climate calculated by the two GCMs for four U.S. regions.

- The model results suggest that daily and year-to-year temperature variability could decrease and precipitation variability could increase. However, the results for temperature are not statistically significant. Furthermore, the two models produce some inconsistent results.

- Results indicate that the diurnal (day and night) cycle may be reduced in the summer, although results for the other seasons are inconclusive.

To determine the validity of the variability statistics of greenhouse gas-perturbed experiments, investigators examined how well the GCMs reproduce present-day climate variability. A comparison of observed and model results for the current climate for the two GCMs for selected U.S. regions reveals interesting contrasts and similarities regarding the reproduction of climate variability. Simulation of variability is reasonably good in several cases.

- Although some discrepancies exist between actual and estimated temperature and precipitation values, the models simulate the seasonal cycles of temperature and precipitation reasonably well in the four regions investigated.

- The models make errors (generally overpredictions) in predicting daily and year-to year temperature and precipitation variability.

Explanations for some discrepancies, such as why the daily temperature variances are too high, relate to how the surface hydrology is modeled in both GCMs (NCAR and GISS). More investigations of model results are necessary to improve understanding of future climate variability changes.

NATURE OF CLIMATE VARIABILITY

Global warming can change the variability of climate. Although less is known about variability than about most other aspects of climate change, it may have greater impacts on some systems than changes in average climate conditions.

Variability is an inherent characteristic of climate (Gibbs et al., 1975) and is closely related to the concept of climate change. However, no clear universally accepted distinction is made between the terms "climate variability" and "climate change." Both terms refer to fluctuations in climate from some expected or previously defined mean climate state. Berger (1980) makes the distinction that climate change refers to a secular trend that produces a change in the average, whereas variability refers to the oscillations about that mean. Distinctions can only be made relative to the time scales of concern. The climate change discussed in this report refers to a change from the mean global climate conditions we have experienced in roughly the past few centuries. On a longer time scale (i.e., thousands of years), however, this climate "change" would be viewed as an instance of climate variability (i.e., as one of many fluctuations around mean conditions prevailing over several thousand years).

For the purpose of this report, climate variability is defined as the pattern of fluctuations about some specified mean value (i.e., a time average) of a climate element. Hence, in regard to the climate change considered here, climate variability refers to fluctuations of climate around the new mean condition that constitutes the climate change, and is expressed on time scales shorter than the time scale of the climate change. For example, if it is assumed that the average annual global surface temperature will be 3°C warmer than it is currently, then the climate variability on a year-to pattern of departures from this mean increase.

One of the main concerns regarding climate change is whether and how climate variability will change (i.e., will the pattern of fluctuations around the new mean at any given location be the same as that around the "old mean"). This concept of changing climate variabilities is illustrated in Figure 3-1, which displays three simulated time series of daily maximum July temperature for Des Moines, Iowa. In all three cases, the mean maximum monthly temperature is the same (i.e., 86.2°F), but the patterns of daily fluctuations about this mean differ significantly. Changes in climate variability refer to the differences in these patterns.

The causes of climate variability depend largely on time scales and may be divided into two major categories: (1) those arising from internal dynamics that produce stochastic (random) fluctuations (and possibly chaotic behavior) within the climate system, and (2) those arising through external forcing of the system. Table 3-1 summarizes different causes of climate variability on different time scales. On very long time scales (e.g., 100,000 years), astronomical factors account for much variability (orbital parameters in Table 3-1).

Variations of climate on a year-to-year basis (interannual variability) can arise from external forcings, such as volcanic eruptions, or from slowly varying internal processes including, as part of the internal system, interactions between the atmosphere and oceans, soils, and sea ice fields. These interactions can result in shifts in locations of major circulation features or changes in their intensity (Pittock, 1980). The largest effect, presumably, is due to variations in sea surface temperatures, such as those occurring in El Niño Southern Oscillation (ENSO) events.

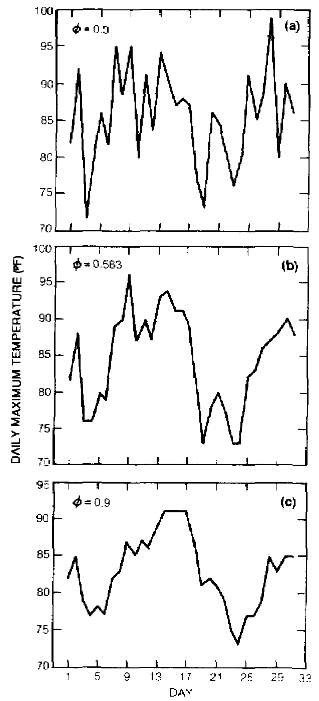
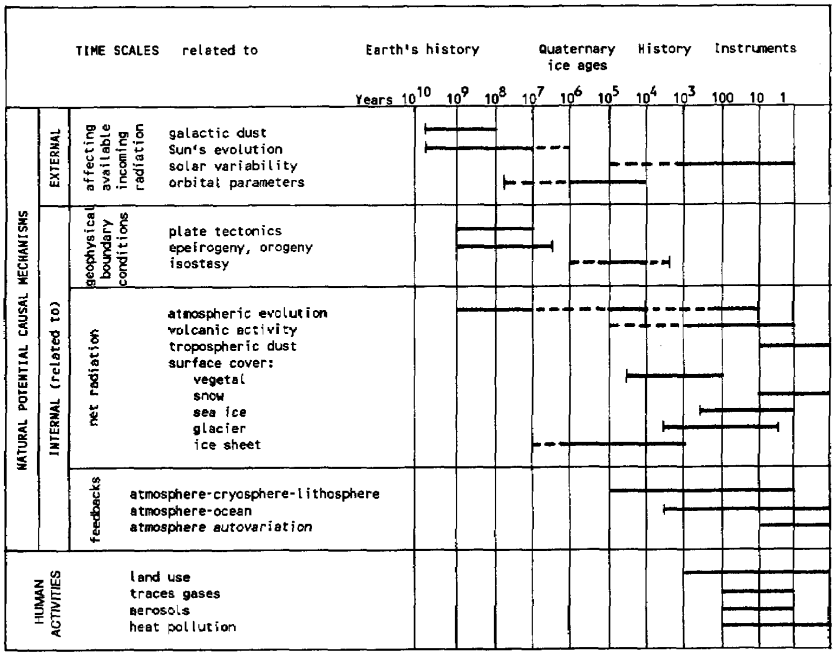


Figure 3-1. Simulated July daily maximum temperature time series at Des Moines, Iowa. All assume the same average temperature but use different statistical estimates (first-order autocorrelation coefficient 0) of variability (Mearns et al., 1984).

Daily variability of a nonperiodic nature largely results from variations in synoptic scale weather processes, such as high- and low-pressure cells and upper-atmosphere wind streams, which direct the movement of such features (atmosphere autovariation in Table 3-1) (Mitchell, 1976). These features interact with local topography to provide location-specific variability. (Variations caused by these weather processes are largely stochastic and internal to the climate system.)

This report mainly discusses variations on time scales of several years or less -- that is, from interannual to daily variability. Climate variability does not have a specific operational statistical definition, but can be described by a constellation of statistical properties other than the mean. The most commonly used measure is the variance (which is the mean of the sum of squared deviations from the mean of a time series) or its positive square root, the standard deviation.

Table 3-1. Major Processes Involved in Climate Fluctuations for Different Time Scales



Source: Berger (1980).

NATURE AND IMPORTANCE OF CLIMATE EXTREMES

Climate variability is experienced on an impact level mainly through the occurrence of extreme climate events. The impact of extreme variability may be the first indication of climate change. It is important to note, however, that change in the frequencies of extreme events (e.g., heat waves, drought) is not synonymous with change in climate variability.

To illustrate this point, an example is presented of a change in the frequency of heat waves in Des Moines in July, defined as 5 consecutive days in the month with maximum temperatures exceeding 95°F. Just changing the monthly mean of the series by 3°F, without changing variability (as measured by the standard deviation and/or autocorrelation), increases the probability of experiencing a heat wave in July from the current level of 6% to 21%. However, the increase can be even more dramatic if the variability is altered as well as the mean. By increasing the persistence in the time series (i.e., the day to day dependence of the daily temperatures) as well as the mean, the probability of a heat wave increases from 6% to 37% (see Mearns et al., 1984, for further details). Hence, changes in the frequencies of extreme events will occur with changes in the mean climate conditions, but this change can be reduced or rendered more extreme by changes in variability.*

The impacts of climate change on society accrue not necessarily from the relatively slow trends in the mean of a climate variable, but rather from the attending shifts in the frequency of extreme events. This issue has already received some attention in the literature where the nonlinear relationship between changes in the mean and extreme events has been examined (e.g., Schwarz, 1977; Parry, 1978; Mearns et al., 1984). However, less is known about this factor than about most other aspects of climate change.

For the purposes of climate impact analysis, extreme climate events may be considered perturbations of climate that result in conditions outside normal ranges that exceed some critical threshold. What constitutes "normal" (i.e., the averaging period) is, of course, a central issue in defining extremes.

Extreme events relevant to climate impacts function on different time scales, depending upon the climate variable involved and the impact area of interest. Thus, events can range from the length of time (in minutes and hours) that minimum temperatures in Florida remain below a critical value, resulting in damage to citrus crops, to the length of time (in months and years) that precipitation is particularly low in California, resulting in serious water shortages for industry and agriculture. The probability of extreme events can also vary considerably -- for example, from that of extreme snowfall in the Buffalo, New York area such as that of the 1976-77 winter (P = 0.0002) (Policansky, 1977), to that of heat waves (temperatures above 100°F for 5 consecutive days) in Dallas, Texas (P = 0.38).

What defines an event as extreme is not only a certain statistical property (for example, likelihood of occurring less than 5% of the time), but also how prepared a particular system is to cope with an event of such magnitude. Hence, very few extreme events have a fixed absolute value independent of particular response systems at a particular location. This implies that what constitutes an extreme event can also change over time because of changes in the relevant response system (Heathcote, 1985).

It is thus very difficult to comprehensively review all climate extremes of importance to society, and what is presented here is far from an exhaustive catalog. Because one of the purposes of this review is to highlight the extreme events of importance that can serve as guides for choosing what extreme events should be quantitatively analyzed in GCM experiments, priority is given to events related to variables that can be relatively easily analyzed.

This review considers the two most important climate variables -- temperature and precipitation -- and their extremes (maxima and minima), and one type of major meteorological disturbance -- severe storm effects. Extremes in these variables affect the areas of energy use and production, human mortality and morbidity, agriculture, water resources, and unmanaged ecosystems (although not all areas are discussed under each climate extreme).

Temperature

Given the scientific consensus that higher atmospheric concentration of greenhouse gases will raise average global temperatures, extreme temperature effects are given priority in this analysis.

Maximum Temperatures

Extreme temperature effects on human mortality and morbidity have received the most attention in the scientific literature (e.g., Kalkstein, Volume G; Becker and Wood, 1986; Jones et al., 1982; Bridger et al., 1976; Ellis, 1972). This is partly because the relevant climate factors (i.e., maximum daily temperatures and relative humidity) are readily available for analysis.

A heat wave is defined as a series of days with abnormally high temperatures (i.e., temperatures exceeding some critical threshold). Examples include the 1980 heat wave in the United States when Kansas City had 17 consecutive days above 39°C (102°F) (Jones et al., 1982), and Dallas had 42 consecutive days with temperatures above 38°C (100°F) (Becker and Wood, 1986). The death toll that year was several times above normal (1,265 lives).

Studies have specifically tried to pinpoint the most significant meteorological factors associated with heat-related death and illness. Jones et al. (1982) determined that high maximum temperatures, the number of days that the temperature is elevated, high humidity, and low wind velocity contributed to excess mortality in Kansas City and St. Louis in the 1980 heat wave. Kalkstein et al. (1987) established that runs of days with high minimum temperatures, low relative humidities, and maximum temperatures above 33°C (92°F) contributed to heat-related deaths in New York City.

Increases in heat waves are virtually certain, assuming global warming. But how they increase (longer or greater departure from the mean) very much depends on changes in variability that would affect the persistence of high temperatures.

Such crops as corn, soybeans, wheat, and sorghum are sensitive to high temperatures during their bloom phases. For example, Shaw (1983) reported that severe temperature stress during a 10-day period around silking (a critical period during which the

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*Although the scenarios created for this study assume no change in variability (see Chapter 4: Methodology) they do assume, for example, increases in heat waves and decreases in cold waves that result from changes in mean climate conditions.

number of kernels on the ear is determined) will result in crop failure. McQuigg (1981) reported that the corn crop was severely damaged in July 1980 as a result of temperatures exceeding 38°C (100°F). The destructive effects of runs of hot days on corn yields were particularly apparent during 1983 in the U.S. Corn Belt. Although the damage from high temperatures is best documented for corn, it has also been noted in wheat and soybean yields (e.g., Neild, 1982; Mederski, 1983).

Although not as much research has been performed on the effects of temperature extremes on natural ecosystems, some research has been done on forest responses to temperature extremes. Solomon and West (1985) indicate in their summary of climate effects on forests that the frequency, intensity, and lengths of heat waves under climate change conditions are important factors influencing seedling survival and can contribute to the loss of a species from an ecosystem. A run of warm years can affect the location of tree lines. Shugart et al. (1986) established that a period of warm summers at high altitudes during the 1930s, when the mean annual temperature was no more than 1°C higher than average, resulted in a burst of regeneration in boreal forest trees near polar and altitudinal limits in North America.

High temperatures have their most immediate impact on energy by causing increased electricity demand for air-conditioning. Using climate scenarios similar to those in this report (see Chapter 4: Methodology), Linder et al. (1987) found that energy demand in New York would significantly increase in summer (on the order of 3% for an average August day in 2015 for the downstate area).

Minimum Temperatures

Extreme minimum temperatures will not necessarily be less of a problem with CO_2 induced climate warming. For example, changes will most likely occur in the growing areas of certain crops, where risks of frost damage may not be clearly known.

The best example of frost damage to crops is the effect of low minimum temperatures on citrus trees. This problem has been studied in depth for the citrus crop in Florida. (See Glantz, Volume J, for a discussion of the Florida citrus industry's responses to freezes in the early 1980s.) The most striking aspect of these freezes is the very short freezing time necessary for damage to occur. New citrus growth (i.e., bloom buds) can be completely killed during a 30-minute exposure to -3.3°C (26°F) or a 3-hour exposure to -2.2°C (28°F). The effect of freezes is exacerbated if the crops have not hardened with the cold. Thus, if a freeze follows a warm period (i.e., indicating high daily temperature variability) when dormancy has been broken, more damage will occur at less extreme temperatures. For example, the December 24-26, 1983, freeze caused the Florida citrus yield to be 30% lower than it had been the previous year (Mogil et al., 1984).

Extreme lows on a seasonal basis tend to most directly affect winter energy use for heating. In the United States, the difference in heating fuel use for a warm as compared with a cold winter can vary by as much as 400 million gallons of oil. During the extremely cold winter of 1976-77, heating degree days (calculated on a base of 18°C (65°F)) were 10% greater than normal for the nation as a whole (Dare, 1981).

Precipitation

Anticipated changes in precipitation resulting from climate change are not well known at this point. However, geographic shifts in rainfall patterns will likely occur. Changes in the frequencies of extremes of both droughts and floods must be considered.

Drought is of particular interest at the time of this writing because of the 1988 drought in the United States and the energetic speculations being made concerning its possible connection with CO_2-induced climate change (Wilford, 1988). It cannot be said that the summer 1988 drought was caused by CO_2 induced climate warming, but rather that such droughts would be possible and perhaps more frequent with such a warming. (In fact, most recent evidence presented by Trenberth et al. (1988) indicates that the cause of the drought was primarily temperature anomalies in the Pacific (i.e,, cool temperatures along the Equator and warmer temperatures to the North), which led eventually to the anomalous displacement of the jet stream northward. These causes are considered to be natural variations in the coupled atmosphere-ocean system.)

Droughts

The most basic, general definition of drought may be lack of sufficient water to meet essential needs (Gibbs, 1984). From a more strictly climatological point of view, it may be considered a condition determined relative to some long-term average condition of balance between rainfall and evapotranspiration in a particular region (Wilhite and Glantz, 1987). Different types of drought are recognized, such as meteorological drought (a departure of precipitation from normal), agricultural drought (insufficient soil moisture based on crop growth needs), or hydrological drought (based on departures from normal or relevant hydrologic parameters, such as streamflow). These "types" of drought are not completely independent, but can show up at different time lags one from the other.

Drought of any kind is anomalous as an extreme climatological event in that it is a "creeping" phenomenon; neither its onset nor its end is clearly punctuated in time. It is difficult to measure drought severity, since drought is a combination of factors: duration, intensity, and areal extent. Drought also can be one of the longer-lived extreme events in that it can be measured in terms of seasons or, more frequently, years.

In the United States, major droughts have usually been defined in terms of several years, and the rate of occurrence is most strongly influenced by interannual variability of precipitation.

The effect of drought on crop production is perhaps the impact of drought that has received the most research attention. The occurrence of droughts has been a major cause for yearly variability in crop production in the United States (Newman, 1978). During the 1930s, drought yields of wheat and corn in the Great Plains dropped to as much as 50% below normal, whereas the drought in the 1950s brought less dramatic declines in yields (Warrick et al., 1975). In 1988, national corn yields were 40% below normal (see Chapter 6: Agriculture).

Soil moisture deficits affect natural vegetation as well as crops. Much of the research in natural ecosystems has been on forests. Soloman and West (1985) identify drought as the cause for death of seedlings and for slowed or stopped growth of mature trees.

Aside from the direct effects of insufficient moisture on unmanaged ecosystems, indirect effects also result from increased incidence of fires. During the drought of 1988, forest fires broke out across the country; the most notable was the devastating August fire in Yellowstone National Park, which blackened 60% of its land area.

The effects of drought on U.S. energy resources are most apparent with regard to hydroelectric power generation. Linder et al. (1987) discussed the effect of decreased streamflow due to drought on the production of hydroelectric power in New York (see Chapter 10: Electricity Demand).

The possibility of combined effects of higher maximum temperatures and drought on electricity demand and supply should be noted. Increased demand (due primarily to increased temperature) would very likely occur when drought would limit generating capacity in regions such as New York and the Pacific Northwest.

Floods

On average, 200 people die each year from flooding; flash floods account for most of these deaths (AMS, 1985). Floods also destroy property, crops, and natural vegetation, and disrupt organized social systems.

Floods result from a combination of meteorological extremes (heavy precipitation from severe storms, such as hurricanes and thunderstorms), the physical characteristics of particular drainage basins, and modifications in drainage basin characteristics made by urban development. Loss of life and property is increasing as use of vulnerable floodplains increases.

The recurrence interval of flooding is most important in applying effective control and protection mechanisms. These include building dams, reservoirs, and levees, and improving channels and floodways (White et al., 1975). For example, flood control reservoirs are designed to operate at a certain level of reliability, and the reliability is determined by a certain flood magnitude that the reservoir can handle, such as a 100-year flood. The statistics of flooding are vital for designing for protection and are based on a certain climate variability determined from the historical record. As that variability changes, the reliability of the protection system will change.

Major recent floods include the following:

1. Rapid City, South Dakota (June 1972), 231 deaths and more than $100 million in property damage;
2. Northeastern United States (June 1972), 120 deaths and about $4 billion in property damage --inundation from Hurricane Agnes;
3. Big Thompson Canyon, Colorado (July 1976), 139 deaths and $50 million in property damage -- a result of a stalled thunderstorm system that delivered 12 inches (305 millimeters) of rain in less than 6 hours (Henz and Sheetz, 1976); and
4. Johnstown, Pennsylvania (July 1977), 76 deaths and $200 million in property damage -- a result of slowly moving thunderstorms that deposited 11 inches (279 millimeters) of rain in 9 hours.

Floods in the 1980s have been less serious in terms of loss of life, but changing frequencies of severe storms, such as thunderstorms and hurricanes, as well as general shifting of precipitation patterns could result in unprecedented losses from floods in a climate-changed world.

Severe Storms - Hurricanes

Three important kinds of weather extremes are present in hurricanes: strong winds, intense and high precipitation amounts, and extreme storm surges. A hurricane is an extreme form of a tropical cyclone, characterized by torrential rains, typically as much as 127 to 254 millimeters (5 to 10 inches) in one storm; high windspeeds, which can exceed 160 kilometers per hour (100 miles per hour); very steep pressure gradients, with pressure at the center as low as 915 millibars (27 inches); and diameters of 160 to 640 kilometers (100 to 400 miles).

Hurricanes are classified according to their severity on the Saffir/Simpson Scale (categories 1 through 5), taking into account the central pressure, windspeed, and surge. Major hurricanes are considered to be all those of categories 3 through 5 wherein central pressure is less than 945 millibars (27.9 inches), windspeeds exceed 176 kilometers per hour (110 miles per hour), and the surge is greater than 2.4 meters (8 feet) (Herbert and Taylor, 1979).

From 1900 through 1978, 53 major hurricanes (averaging two major hurricanes every 3 years) directly hit the United States. Overall, 129 hurricanes of any strength hit the United States (averaging approximately two each year). In recent decades, the number of major hurricanes has declined. From 1970 to 1978, only three hurricanes occurred, compared with six or more in earlier decades. The last hurricane of category 4 or 5 to strike the United States was Hurricane Camille in 1969. In 1980, Hurricane Allen, which at one time reached force 5, weakened before it struck a relatively unpopulated segment of the Texas coast (Oliver, 1981). Since then, the population of the south coastal regions of the United States has grown tremendously, and most inhabitants have never experienced a major-force hurricane. Building in coastal areas has also increased with population, which raises the potential for high property damage. Thus, the population may be more vulnerable and less prepared to handle this particularly devastating extreme event (Sanders, 1982).

Any increase in the frequency and/or intensity of these storms, which could result from climate change, would be of great concern to southern coastal regions of the United States. Hurricane Gilbert, which occurred in September 1988, reinforced this concern, even though it did not cause major damage to the coastal United States. Hurricane Gilbert may well prove to be the most powerful hurricane of the 20th century; its lowest central pressure (883 millibars or 26.13 inches) was the lowest ever measured in the Atlantic Gulf and Caribbean regions of tropical storm activity. Serious damage did occur primarily in Jamaica, the Cayman Islands, and the northern tip of the Yucatan Peninsula (Ludlum, 1988).

Coleman (1988) has found in the historical record some limited evidence for increased frequency for the number of storms formed in the North Atlantic during years of warmer-than-average sea surface temperatures. Emmanuel (1987) has found through a hurricane modeling experiment that the intensity of hurricanes increases under warmer conditions. The extreme intensity of Hurricane Gilbert in September 1988 is consistent with the findings. Emmanuel (1988) also asserts the importance of establishing a general theory of hurricane development independent of current atmospheric conditions, so that scientists can predict changes in frequency and intensity of storms with climate change.

STUDIES OF CHANGING CLIMATE VARIABILITY

Empirical Studies

One of the methods available for gaining some insight into how climate variability may change in a generally warmer climate is to investigate the climate record for past relationships between mean climate change and changes in variability. However, past research efforts to determine changes in climate variability and relationships with changes in mean climate conditions have not resulted in a clear consensus.

Van Loon and Williams (1978) found significant differences in interannual temperature variability in North America during two different 51-year periods. However, they found no single connection between trend in temperature and trend in its interannual variability. Specifically, they assert that their results do not support the postulated association between cold periods and high variability of temperature. Diaz and Quayle (1980), in a thorough analysis of the U.S. climate (temperature and precipitation), found no systematic relationship between changes in mean temperature and precipitation and their corresponding variances.

Brinkmann (1983) analyzed the relationship between mean temperature and variability in Wisconsin using climate data for three stations. She found no relationship between mean temperature and interannual variability, but did find a negative correlation between winter mean temperatures and the day-to-day variability, and a corresponding positive relationship for summer conditions. What thus means is that cold winters are more variable than warm winters, but that cool summers are less variable than warm ones. Brinkmann explains these relationships on the basis of Wisconsin's location with respect to general circulation patterns.

Lough et al. (1983) analyzed the association between mean temperature and precipitation and variability in Europe by using the analog approach to create climate change scenarios (the analog approach is further discussed in Chapter 4: Methodology). They selected two periods when arctic temperatures were particularly warm and cold (1934-53 and 1901-20). Results indicate that the regions of lower winter temperatures roughly coincide with the region of increased variability, but the coincidence is far from perfect.

These studies indicate that significant changes have occurred in both interannual and day-to-day climate variability in historical times, but that simple or distinct relationships between changes in mean climate conditions and changes in variability have not been established. Moreover, the value of seeking such relationships in the past as a key to the future is potentially limited, since the causes of very short-term warming or cooling in the past are not known, but in any event, are not caused by increases in greenhouse gases.

The failure of the analog approach to provide an empirically consistent and causally coherent scenario of possible changes in climate variability contributes to the necessity of examining climate variability in climate modeling experiments. As discussed in Chapters 2 and 4, GCMs have limitations, but they have one clear strength over empirical attempts to analyze future climate change: the modeling experiments are constructed such that the response of the climate system to the true cause of the change (increased greenhouse gases in the atmosphere) is simulated.

Modeling Studies

Studies comparing variability statistics of observed time series with variability statistics of GCM-generated time series of climate variables relevant to climate impacts are not numerous in the atmospheric sciences literature, although studies first appeared in the early 1980s (e.g., Manabe and Hahn, 1981; Chervin, 1981). Such studies are critical if climate change research is to determine whether the variability statistics of doubled CO_2 experiments with GCMs are valid. To accomplish this, the ability of GCMs to reproduce present-day climate variability statistics must be examined, and a thorough understanding of discrepancies must be attained.

Chervin (1986) used the National Center for Atmospheric Research Community Climate Model (NCAR CCM) to investigate interannual climate variability and climate prediction. He focused on the additional variability attributed to external boundary conditions (i.e., in this modeling context, external boundary conditions refer to important conditions outside the atmosphere that cause changes to the atmosphere but are not in turn affected by it, such as sea surface temperatures). He eliminated sources of external variability in the model, such that discrepancies between modeled and observed variability would reflect this external component. The variability of mean sea level pressure and 700-millibar geopotential height (which roughly corresponds to the height above the surface where the atmospheric pressure equals 700 millibars, and is related to large-scale wind patterns) were analyzed for the Northern Hemisphere, with particular focus on the United States. Results, however, indicated no significant differences between modeled and observed variabilities of mean sea level pressure over the United States and only limited areas of differences in the variability of 700-millibar geopotential height.

Bates and Meehl (1986) also used the CCM to investigate changes in the frequency of blocking events (stationary pressure systems that block the flow of upper air currents in the atmosphere) on a global scale under doubled CO_2 conditions. Blocking events are strongly related2 to persistent surface temperature anomalies, such as heat waves in the summer. They found that the model generally produces too few extreme blocking events. Under doubled CO_2 conditions, standard deviations of blocking activity were found to mainly decrease in all seasons (i.e., the variability of blocking events decreased).

Two studies were recently conducted on local or regional scales using the U.K. Meteorological Office five-layer GCM. Reed (1986) analyzed observed versus model control run results for one gridpoint in eastern England. Compared with observations, the model tended to produce temperatures that were too cool and variability that was too high as measured by the standard deviation. For precipitation, the model produced too many rain days but did not successfully simulate extreme rain events of greater than 20 millimeters per day.

More recently, Wilson and Mitchell (1987) examined the modeled distribution of extreme daily climate events over Western Europe, using the same model. Again, the model produced temperatures that were too cold, and hence, extreme minimum temperatures were overestimated. This problem was most pronounced in grid boxes away from the coasts. The model also produced too much precipitation in general, did not successfully reproduce observed highest daily totals, and overestimated the number of rain days. Wilson and Mitchell examined changes under quadrupled CO_2 conditions and found that variability of temperature generally decreased.

Hansen et al. (1988) used the Goddard Institute for Space Studies (GISS) general circulation model to simulate the global climate effects of time-dependent variations of atmospheric trace gases and aerosols. It was determined that the model only slightly underestimates the observed interannual variability across the globe. However, the model's variability tends to be larger than that observed over land (i.e., only considering land areas, not ocean areas).

Among the calculations made with output from the transient run were changes in the frequencies of extreme temperature events. This was accomplished by adding the model-induced temperature change with climate warming to observed local daily temperatures, assuming no change in variability. Results indicate that predicted changes in the frequency of extremes beyond the 1900s at locations such as New York, Washington, and Memphis become quite large and would have serious impacts.

The studies reviewed above indicate some important shortcomings of GCMs with regard to their ability to faithfully reproduce observed variability statistics. More research is clearly needed to further determine the sensitivity of the models to changes in physics, resolution, and so forth, with regard to the determination of variability. Moreover, only one of these studies explicitly concerns variables of importance to climate impact analysis. Studying the higher moments (e.g., variance) of climate variable statistics, and carefully verifying the models' ability to reproduce observed variability on regional scales, are the necessary prerequisites to rigorously analyzing possible changes in these statistics under doubled CO_2 conditions.

STUDIES FOR THIS REPORT

Two research efforts were undertaken for this report to attempt to increase knowledge concerning how climate variability may change. The climate change scenarios used in the climate change impact studies reviewed in this report excluded consideration of changes in variability (see Chapter 4: Methodology). The following two studies on GCM estimates of current and future variability were performed for this report:

- Variability and the GISS Model - Rind, Goldberg, and Ruedy, Goddard Institute for Space Studies (Volume I); and
- Variability and the NCAR Model - Mearns, Schneider, Thompson, and McDaniel, National Center for Atmospheric Research (Volume 1).

It should be recalled that scenarios of climate change generated by the GISS GCM are used in most of the impact studies summarized in this report. The results of these two studies are directly compared in a later section.

The GISS Study

Rind et al. (1989) examined how well the GISS GCM simulates the observed variability of climate by comparing the model and the observed interannual and daily variations of temperature and precipitation. They described the model assessment of changes in variability for these two major climate variables, under climate change using the GISS doubled CO_2 run (8° x 10° resolution) and the transient climate change experiment in which trace gases were increased gradually. The analysis was conducted for the Great Plains, the Southeast, the Great Lakes region, and California (see Figure 3-2). Observed data consist of the average of observations at nine different stations per grid box.

First, mean conditions were compared for actual weather observations with the GCM control run (or single CO_2), the doubled CO_2 run, and the transient run. The model values for mean temperatures for four months in the four regions are generally cooler than observations (particularly in summer and fall), but only by a few degrees Celsius. Model precipitation values are fairly close to observed values in the Great Lakes and Southeast grid boxes, but model values are higher than observed for the other two regions (e.g., January in the southern Great Plains: model = 2.1 millimeters per day, observed = 0.46 millimeters per day). Under the doubled CO_2 scenarios, temperatures increase over the control run by 4 to 6°C (7 to 11°F) in the winter and 3 to 4°C (5 to 7°F) in the summer. Warming in the transient scenarios is progressive, but temperature changes more gradually than with simply doubling the CO_2 amount. Winter warms more than summer, and so the annual seasonal cycle is reduced under climate change. Precipitation changes are not statistically significant at individual grids, but there is an overall tendency for increased precipitation.

Interannual Variability

Standard deviations of temperature and precipitation of observed and modeled data were compared for all months. In most months, the model year-to-year temperature variability is similar to the observed variability in the four regions, but in summer the variability was overestimated by 0.3 to 0.6°C (0.5 to 1.1°F). Precipitation variability is overestimated in half the cases where precipitation amount is also overestimated. The relative annual variability of precipitation (that is, the standard deviation relative to the mean) of the model is generally in agreement with observations.

Under conditions of climate change (doubled CO_2), comparing control versus climate change, there is generally reduced variability of temperature from January through April. Results for other seasons of the year are more ambiguous. For precipitation, the doubled CO_2 climate resulted in increased variability in most months at the four grids (in 31 of 48 cases), but was particularly striking at the Southeast grid. These changes, however, were often of the same order as the model's natural variability (from examination of the 100-year control run). The sign of the change in mean value and the sign of change in interannual variability are highly correlated.

Daily Variability

Daily variability of temperature was analyzed by taking the daily departures from monthly means and comparing the resulting model distribution with the distribution formed in the same manner from the observational data.

Ten years of control run for the transient experiment for four months (January, April, July, and October) were compared with 30 years of observations. Distributions of observed versus modeled daily temperature data were, in general, not significantly different. Comparisons were also made by calculating the standard deviations of the departures from the mean for the four months (Table 3-2). These results indicate that the model's values are significantly greater than the

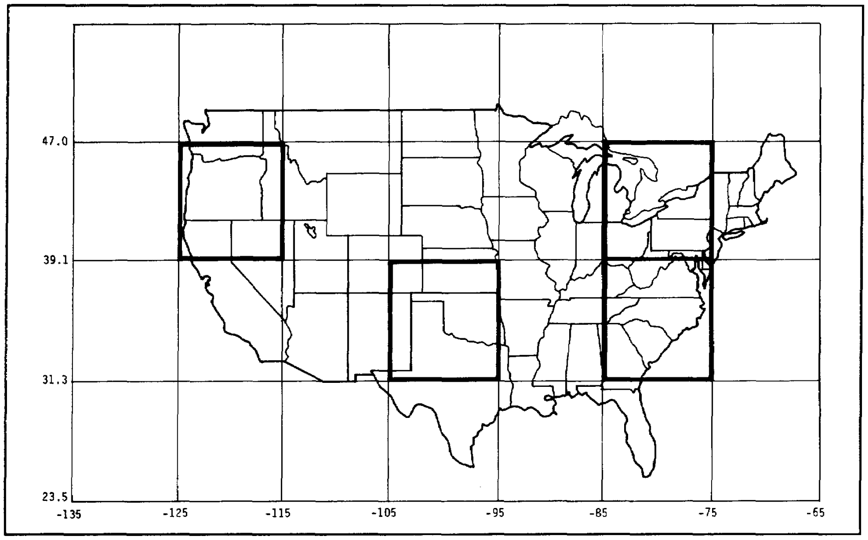

Figure 3-2. The locations of the four GISS model grids.

observed values, which demonstrates that the model is producing too many extremes.

Results in Table 3-2, comparing standard deviations, indicate that although changes with time are not strictly progressive, most cases by the end of the climate change experiment show reductions in the standard deviation although these reductions are not statistically significant. (Note in Table 3-2 that standard deviations for the future decades are changes in standard deviation (SD): model current SD minus future decade SD) Since the results are not statistically significant, a decrease of daily temperature variability is not demonstrated.

For precipitation, comparisons are more complex. For example, the number of observation stations used to represent a grid box does affect the results. Model rainfall distributions differ significantly from observed distributions in half the cases (in three seasons for California and the southern Great Plains). The model also produces fewer days of light rain in general and more extreme values in the winter in all four regions (Table 3-3).

In the transient experiment, the precipitation distributions differ from the control climate about one-fourth of the time with no general progression over the decades. Figure 3-3 presents a sample set of distributions for precipitation during several decades of warming for the West Coast in April. In comparing standard deviations (Table 3-3), the warmest time period exhibits increases in standard deviations in half of the cases. These results are again consistent with those for interannual variability.

Variability of the Diurnal Cycle

It would be expected that the diurnal cycle would decrease under changed climate as the additional greenhouse gases could limit nighttime cooling. Comparisons of control model results with observations are reasonable in the four regions. Under doubled CO_2 conditions, it was found that the amplitude of the diurnal cycle very definitely decreases in summer but changes inconsistently in the other seasons. The reason for this is the dominance of radiative heating in the summer and of other forms of heating and cloud cover change in other seasons.

The NCAR Study

In this study, Mearns et al. (1989) analyzed mean and variance of climate variable time series from selected empirical stations and those produced by general circulation model control and doubled CO_2 runs. They attempted first to determine how faithfully the GCMs reproduce these measures of the present variability and then to examine how the variability is estimated to change in CO_2-perturbed cases. By comparing the relative performance (i.e., model versus observations) of various versions of the NCAR CCM (i.e., versions with different physical parameterizations

Table 3-2. Daily Temperature Standard Deviations (SD) (°C)

Month	Location	Observed SD	Model Current SD	2010 s *▲SD	2030 s ▲SD	~2060 ▲SD
January	Southern Great Plains	4.81	8.15	0.61	-1.19	-0.83
	Southeast	4.53	6.90	-0.14	-1.14	-0.23
	West Coast	3.63	5.86	0.61	0.05	-0.16
	Great Lakes	4.97	5.79	0.44	-0.33	-0.44
April	Southern Great Plains	3.72	5.77	-0.57	-0.27	-0.80
	Southeast	3.71	5.50	-0.65	-1.61	-1.24
	West Coast	2.59	4.29	0.77	0.60	0.33
	Great Lakes	4.65	6.15	-0.51	-0.26	-1.39
July	Southern Great Plains	1.74	2.56	0.54	-0.19	0.18
	Southeast	1.50	2.34	0.14	-0.22	-0.24
	West Coast	2.40	3.56	0.03	0.54	0.28
	Great Lakes	2.38	3.02	-0.48	-0.84	-0.14
October	Southern Great Plains	3.79	5.16	1.16	0.97	1.35
	Southeast	3.59	5.21	-0.54	-0.25	-0.73
	West Coast	3.15	6.51	-0.55	-0.30	-0.80
	Great Lakes	4.09	5.46	-0.37	0.91	-0.06

*▲SD = Change in standard deviation (model current - future decade).
Source: Rind et al. (Volume I).

Table 3-3. Daily Precipitation Standard Deviations (SD) (mm/day)

Month	Location	Observed SD	Model Current SD	2010 s *▲SD	2030 s ▲SD	~2060 ▲SD
January	Southern Great Plains	1.08	2.80	0.05	0.05	1.68
	Southeast	4.35	4.62	-1.20	-1.35	-0.85
	West Coast	3.23	4.55	-0.18	0.34	0.13
	Great Lakes	2.23	4.06	-1.07	-0.94	-0.50
April	Southern Great Plains	2.51	3.26	0.94	1.99	1.17
	Southeast	4.35	3.85	0.95	-0.15	0.81
	West Coast	1.41	2.76	0.07	1.02	-0.12
	Great Lakes	3.85	3.29	-0.43	-0.31	0.44
July	Southern Great Plains	2.79	3.08	-0.10	-0.09	0.36
	Southeast	4.13	3.31	0.28	0.29	0.11
	West Coast	0.57	1.53	0.44	0.24	0.71
	Great Lakes	3.68	2.48	-0.06	0.72	0.35
October	Southern Great Plains	2.75	1.79	0.52	0.34	0.00
	Southeast	3.77	3.88	0.72	-0.15	-0.28
	West Coast	1.86	2.69	1.20	-0.63	1.34
	Great Lakes	3.58	2.26	0.52	0.76	0.95

*▲SD = Change in standard deviation (model current - future decade).
Source: Rind et al. (Volume I).

or formulations), Mearns et al. helped to determine what formulations may be needed for forecasting certain measures of variability and how much credibility to assign to those forecasts.

Methods

This study used the output from control runs of three different versions of the NCAR Community Climate Model (CCM). These versions use different parameterizations of important physical processes in the model, such as surface hydrology. The Chervin version (Chervin, 1986) is the primary one used for comparison of observed and model control output (i.e., model runs to simulate the actual present-day climate), since it has the longest time integration (20 years).

The CCM is a spectral general circulation model originally developed by Bourke and collaborators (Bourke, 1974; Bourke et al., 1977), which has been modified by the incorporation of radiation and cloud parameterization schemes. The model has a resolution for physical processes (i.e., grid box size) of approximately 4.5 degrees in latitude and

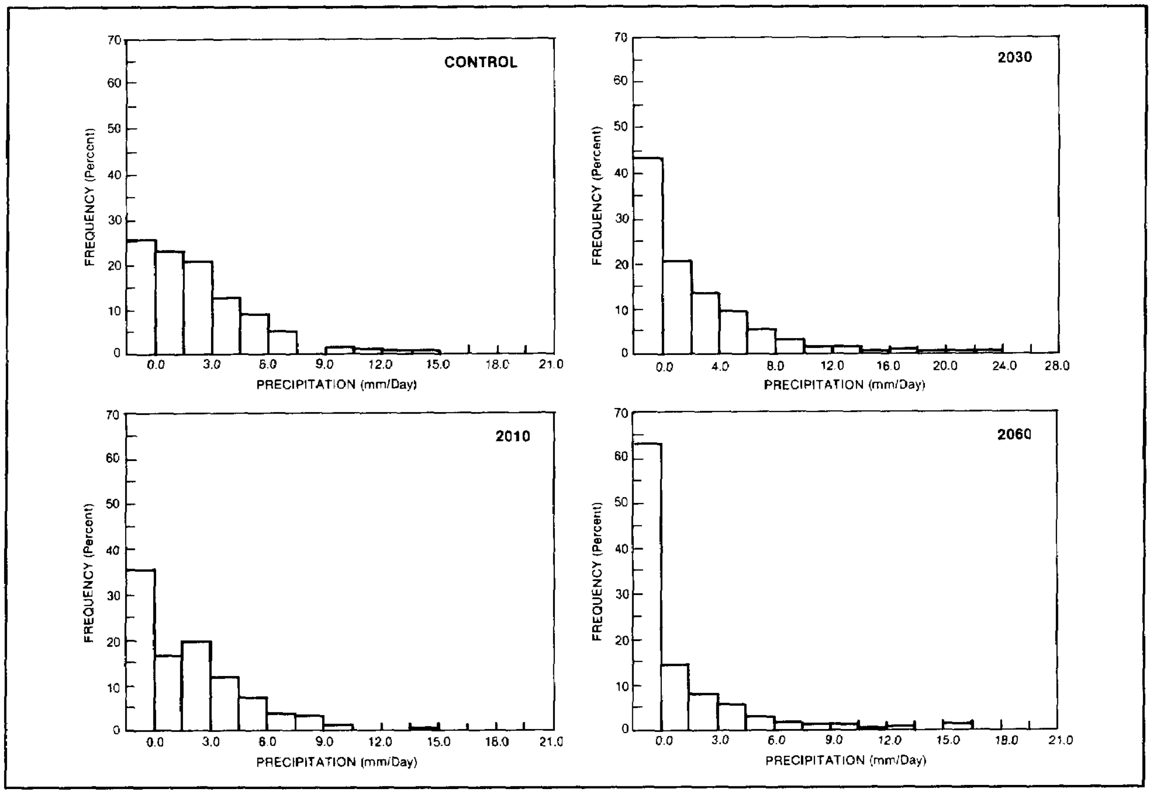

Figure 3-3. Sample of set precipitation distributions for the West Coast in April for specified years of the transient run (Rind et al., Volume I).

7.5 degrees in longitude, and has nine levels in the vertical.

The other two versions of the CCM used are the Washington version (Washington and Meelll, 1984), which includes an interactive thermodynamic ocean and surface hydrology; and the Dickinson version (Dickinson et al., 1986), a version of the more sophisticated CCM1 containing a diurnal cycle and a very sophisticated land surface package, the Biosphere-Atmosphere Transfer Scheme (BATS).

This model calculates the transfer of momentum, heat, and moisture between the Earth's surface and atmospheric layers, and includes a very detailed surface hydrology scheme that accounts for vegetation type and amount, and water use by the vegetation.

The four regions of the United States chosen for investigation were roughly the same as those chosen for the GISS study: the Great Plains (GP; represented by three grid boxes), the Southeast (SE), the Great Lakes (GL), and the West Coast (WC). The locations of the grid boxes and observation stations are indicated on Figure 3-4.

Comparison of Observed versus Chervin Control Run

Four variables deemed particularly relevant to climate impact analysis were chosen for this analysis: daily mean temperature, daily total precipitation, mean daily relative humidity, and mean daily absorbed solar radiation.

Temperature

Figure 3-5 displays the time series of daily average temperature for modeled and observed data for the four regions investigated. The model successfully simulates the annual cycle for the four regions, which represents the seasonal variability.

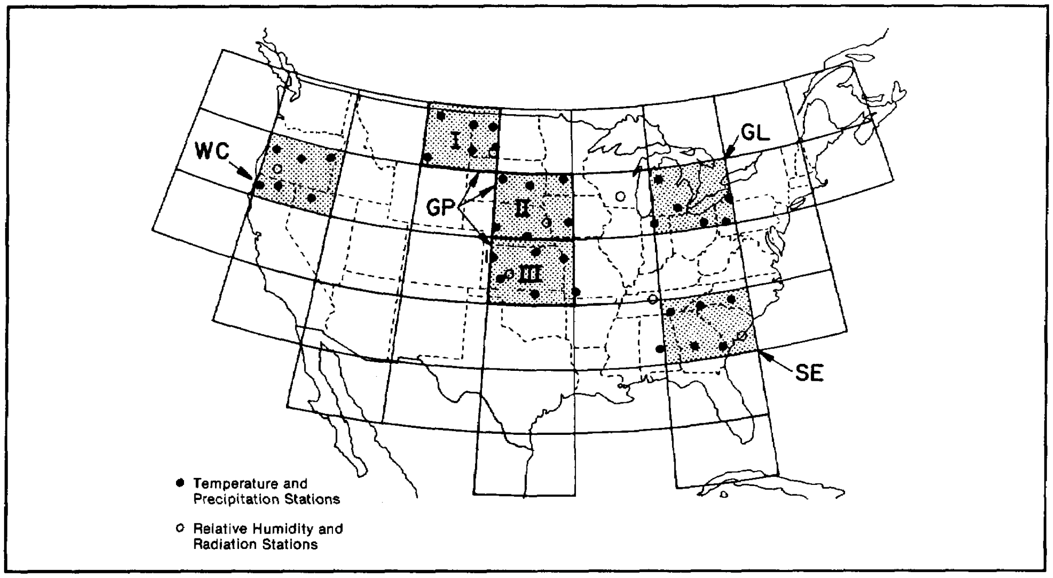

Figure 3-4. NCAR model grid cells and station locations.

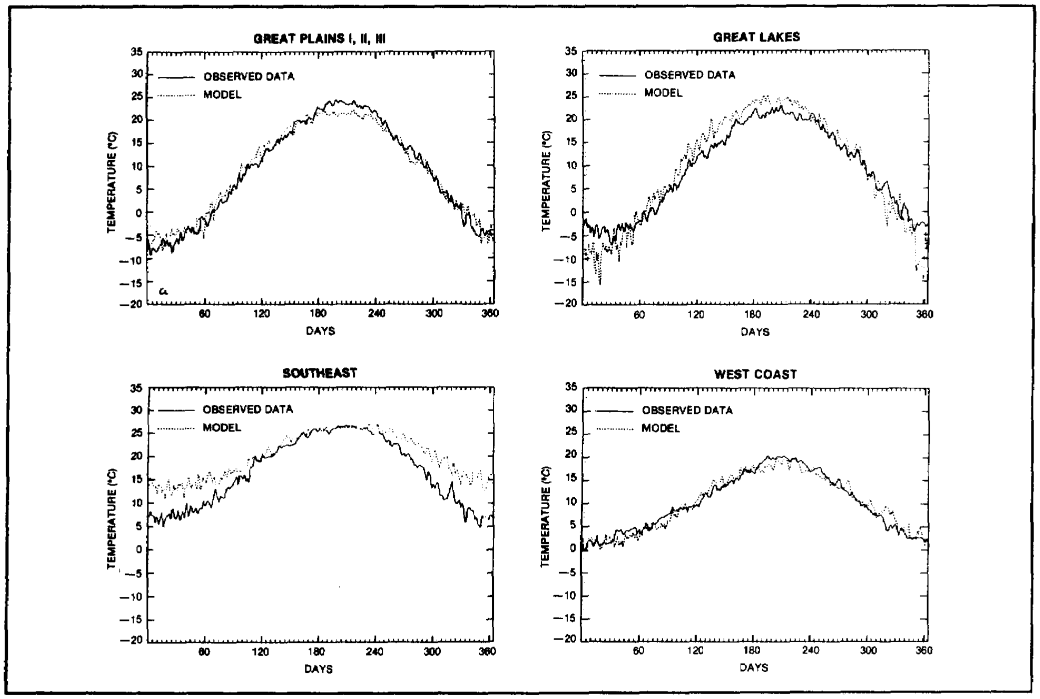

Figure 3-5. Average temperature for a 20-year average year (NCAR model and observations) (Mearns et al., Volume I).

Solar Radiation and Relative Humidity

Simulation of solar radiation ranges from very good (the Great Plains region) to only fair at the Southeast, where the model consistently overestimated absorbed solar radiation during all months. The Chervin CCM is poor at simulating the annual cycle of relative humidity at all four locations

Precipitation

The Chervin CCM consistently overestimates precipitation, although the seasonal cycle is well simulated in the Great Plains region and the West Coast grid. The authors do not know why the model overestimates precipitation, but speculate that it may partly be a result of a precipitation parameterization criterion of 80% relative humidity.

Variability Comparisons of the Chervin CCM

Interannual variability of temperature is generally underestimated by the Chervin CCM in all four regions. Interannual variability of precipitation (i.e., relative variability, the standard deviation relative to the mean) is generally in reasonable agreement with observed data, although it is occasionally overestimated. This is a particularly encouraging result for the credibility of predicting climate changes, given how inaccurate the control precipitation results are in terms of absolute values.

In terms of daily variance, the model's relative humidity tends to be much less variable than observed values at all locations and in most months. Results for temperature for January and July indicate that the Chervin model generally overestimates daily temperature variance.

Intercomparisons of Three CCM Versions and Observed Data

Comparing different model versions' simulations of present-day climate facilitates understanding of the possible ranges of errors and the effect of a model's structural differences. The present-day climate runs of models incorporating physics different from those of the CCM version of Chervin (1986) are compared. Both the Washington and Dickinson runs consist of 3-year integrations.

There is considerable variability in how well the models reproduce mean total precipitation for the four grids, ranging from the relatively good results of Dickinson's model, to the fair results of Washington's model, to the overestimation of Chervin's model. On the basis of mean annual and seasonal comparisons, no one model is clearly superior to the other two in accurately reproducing mean climate (temperature and precipitation) at the four locations.

The Dickinson model most accurately reproduces daily variability of temperature, while the other two models overestimate it. This result is graphically illustrated in the temperature histograms (three models and observed) for two key months for the Southeast grid (Figure 3-6).

The reasons for these discrepancies have yet to be explored in depth, but are likely related to different land surface packages in the models. A possible explanation for the lowered daily temperature variability of the Dickinson model concerns the more sophisticated surface energy balance used, which includes consideration of soil heat capacity.

Control Versus CO_2-Perturbed Runs

The authors included a preliminary analysis of changes in precipitation and temperature, under a scenario of doubled CO_2, using the output from Washington's control and doubled CO_2 runs for the four regions. Interannual variability could not be analyzed because the time series are too short. However, they examined the daily variability of temperature and precipitation.

An annual temperature increase of about 2 or 3°C (4 to 5°F) occurs at all locations. Annual total precipitation increases between 22 and 26% at three locations but decreases slightly (2%) in the Southeast. There are also potentially important changes in the seasonal distribution of precipitation. For example, at the Southeast grid a smaller percentage of the annual total occurs during the summer in the CO_2 perturbed case (from 13 to 6%).

Statistics comparing the daily temperature variance of the control and perturbed runs for January, April, July, and October indicate that the temperature variance in general does not significantly change (at the 0.05 level of significance) at these four grids. Without consideration of statistical significance levels, results are mixed with both increases and decreases.

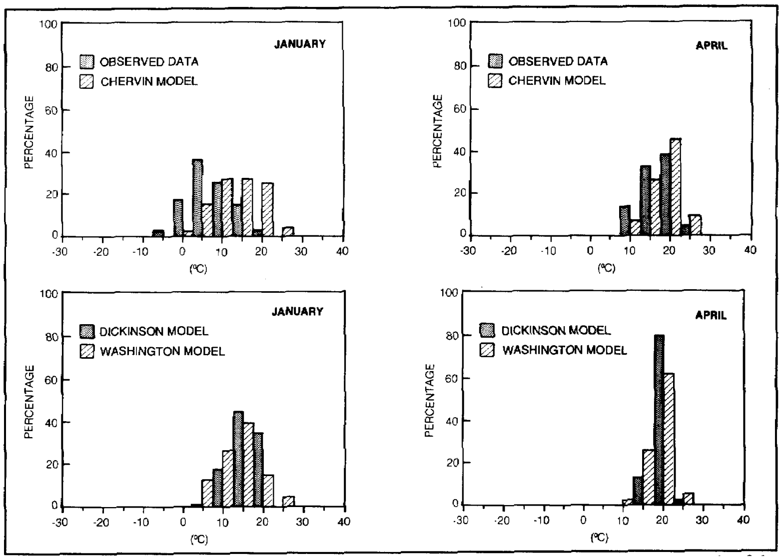

Figure 3-6. Histograms of daily temperature, observations and three model versions, for two key months of the Southeast grid (Mearns et al., Volume I).

The percentage of rain days decreases in the summer under climate change in three of the four grids. Overall, there is a tendency for increased daily precipitation variability at the four locations, based on analysis of precipitation distribution characteristics.

COMPARISON OF GISS AND NCAR RESULTS

It is difficult to compare the two studies. The modeling experiments were conducted partly with different purposes in mind using two different models (which differ not only in how physical processes are modeled but also in their spatial resolutions). They also use different qualitative and statistical methods for making comparisons. The GISS experiment was aimed primarily at examining the changes in variability with climate change, whereas the immediate purpose of the NCAR experiment was primarily to examine and explain discrepancies in variability between model control runs and observations. Since the spatial resolutions of the models differ, the grid boxes of the models do not coincide, and so the regions analyzed differ. These are only some of the problems that would affect these comparisons. Nevertheless, an attempt is made here to compare some of the results that roughly coincide. Some regions, such as the Great Lakes grids, coincide fairly well (see Figures 3-2 and 3-4), and some similar analyses were conducted.

A brief comparison is made of how the models reproduce the observed mean climate. In general, the GISS model is too cool and the NCAR models) too warm. The GISS model overestimates precipitation at two grids, and the Chervin version of the NCAR model overestimates precipitation at all grid boxes (although this is not true of two other versions of the NCAR CCM).

The following sections compare the observed, control, and perturbed runs of interannual and daily variability of temperature and precipitation. Table 3-4 summarizes the comparisons between the modeled control runs and observations for variability.

Interannual Variability

Rind et al. used a 100-year control run for interannual variability calculations. Their observational data set consists of 30 years (1951-80). The NCAR study uses a 20-year control run of Chervin (1986) and a 20-year observational data set (1949-68). The differences in sample size should be noted.

Table 3-5 presents the relevant results, winter and summer standard deviations for temperature, and annual coefficients of variation (i.e., a measure of relative variability) for precipitation for the four regions for both studies. Relative variability values (standard deviation relative to the mean) for the GISS study were provided by its authors (Rind, personal communication). Both models overestimate the temperature variability of the Great Plains region in winter. (However, the difference in the NCAR study was deemed to be statistically insignificant.) Both models underestimate the temperature variability (but the NCAR model much more so than the GISS) for the West Coast winter. In summer, the GISS model overestimates, and the NCAR model underestimates temperature variability at all locations.

Regarding the relative variability of precipitation (measured by the coefficient of variation), the results for the two models are rather similar. The differences between observed and model values are very close (from 1 to 6 percentage points) in each study. The NCAR model slightly underestimates the variability at each location, whereas the slight errors in the GISS results are mixed.

The reasons for the lack of agreement in the two studies are far from obvious, and speculation can only be rough. Certainly the difference in how the atmosphere-ocean interaction is modeled may play a role (i.e., the NCAR model uses fixed sea surface temperatures, whereas the GISS model computes sea surface temperatures from a simple ocean mixed-layer model).

Daily Variability

Daily variability of temperature can be compared for two season months (January and July) at the four locations using the standard deviations (Table 3-6). Because of certain problems concerning necessary statistical assumptions for quantitative testing, these comparisons must be viewed strictly qualitatively.

Table 3-4. Variability Results for Control Runs vs. Observations[a]

Model	Interannual		Daily	
	Temperature	Precipitation (Relative/Absolute)[b]	Temperature	Precipitation (Relative/Absolute)
GISS	High	Good/High	High	Good/High
NCAR[c]	Low	Good/High	High[d]	Good/High

[a] Values in chart refer to how the model estimates compare to the observations.

[b] Relative/absolute refers to comparison of coefficients of variation (relative) and standard deviation (absolute).

[c] Chevrin version of the NCAR model.

[d] Values are good or slightly low for the Dickinson version of the NCAR model.

Table 3-5. Interannual Standard Deviations, Temperature and Coefficient of Variation, Precipitation, GISS, and NCAR Control Runs

Model and region		Temperature (°C) standard deviation		Precipitation coefficient of variation (%) (standard deviation/mean)
		Dec. - Feb.	June - Aug.	
GISS (n=100)				
SGP	Model	1.65	1.05	15
	Obs.	1.20	0.75	21
SE	Model	1.65	1.05	22
	Obs.	1.65	0.70	18
WC	Model	1.35	1.35	18
	Obs.	1.45	0.75	23
CL	Model	1.35	1.25	18
	Obs.	1.50	0.70	18
NCAR (n=20)				
GP III	Model	1.3	0.62	17
	Obs.	1.1	1.20	22
SE	Model	1.0	0.38	10
	Obs.	1.8	0.74	12
GL	Model	2.2	0.71	10
	Obs.	1.6	0.88	11
WC	Model	0.8	0.76	17
	Obs.	1.6	0.81	17

Abbreviations:
SGP = Southern Great Plains; SE = Southeast; WC = West Coast; GL = Great Lakes; GP = Great Plains.
Source: Rind, personal communication; Mearns, et al. (Volume I).

In seven of the eight cases, the studies agree that the models overestimate daily temperature variability.

In both studies, explanations for the overestimations are related to the modeling of surface hydrology (i.e., both models fail to completely account for important surface-atmosphere interactions that would tend to reduce daily temperature variability). (The relative success of the Dickinson version of the CCM in reproducing daily temperature variability partially supports such an explanation, since it has a more sophisticated surface hydrology scheme compared with the Chervin version.)

The models produce, in the majority of cases, too few light rain days. The GISS model produces too many extreme rain events in winter at all locations. The NCAR model tends to produce too many high extremes in all four seasons. Neither study accounts for these discrepancies.

Comparison of Climate Change

Comparison of climate change results of the two models is restricted to changes in daily temperature variability and daily precipitation variability for four months for the four locations, since the NCAR study includes a quantitative analysis of only daily variability change.

Table 3-6. Daily Temperature Standard Deviations (°C)

Month	GISS		NCAR	
	Obs.	Model	Obs.	Model
January				
Great Plains	4.81	8.15	6.18	8.84
Southeast	4.53	6.90	5.41	5.92
Great Lakes	4.97	5.79	5.50	11.20
West Coast	3.63	5.86	4.10	5.00
July				
Great Plains	1.74	2.56	2.90	2.79
Southeast	1.50	2.34	1.55	1.70
Great Lakes	2.38	3.02	2.67	2.82
West Coast	2.40	3.56	2.18	3.52

Source: Rind et al. (Volume I); Mearns et al. (Volume I).

The two studies do not agree on the direction of change of daily temperature variability. The NCAR results are mixed, showing both increases and decreases, although most of these changes are statistically insignificant. Rind et al. conclude that in general, there is a decrease in daily temperature variability on the basis of changes in standard deviations (but the changes are not statistically significant). On the basis of the two research reports, no clear statement may be made about changes in daily temperature variability under CO_2 warming conditions.

A slightly clearer picture is gained from comparison of results for daily precipitation. The results of both models point to increased daily precipitation (although not from analysis of the same statistic). This is not true for all locations during all seasons, however.

Table 3-7 summarizes the very tentative conclusions that can be drawn given all climate change results regarding changes in climate variability from the GISS and NCAR studies. The degree of uncertainty in these conclusions should be noted, as should the observation that many of the results are from only one model (GISS).

Limitations of the Two Studies

Both studies underline the importance of viewing the climate change results of the models in the context of how well they reproduce the present climate. Model deficiencies can be expected to limit the reliability of climate change results, and faith in quantitative results is probably misplaced.

A major model deficiency is inability to resolve subgrid-scale atmospheric phenomena that contribute to climate variability, such as fronts and intense cyclones (hurricanes), and important variations in atmosphere-ocean coupling, such as El Niño Southern Oscillation (ENSO) events. (However, it appears that more sophisticated GCMs incorporating complete ocean models do produce ENSO-type events (Meehl, 1989).) However, model results do give crude estimates as to the importance of some physical processes responsible for variability and what must be done to improve them. Further testing is needed to determine how the models' deficiencies in reproducing present-day climate affects "predictions" for a CO_2-warmed future climate.

Table 3.7. Summary of GISS and NCAR Model "Scenarios" for Direction of Variability Changes from Present Climate to Doubled CO_2 Climate for Four U.S. Regions.

	Variability Results CO_2-Perturbed Runs	
Variable	Interannual	Daily
Temperature	↓?	↓??
Precipitation	↑?	↑??

[a]Question marks indicate degree of uncertainty:
? = results of only one model;
?? = results of two models, but some conflicting results.

IMPLICATIONS FOR STUDIES OF CLIMATE CHANGE IMPACTS

As indicated in the second section of this chapter, virtually all systems affected by climate are affected by climate variability, although some are more affected than others. The relative importance of climate variability and changes in variability, as a result of climate change, to particular impact areas is reflected in the results and limitations of some of the studies summarized in this report.

Of greatest concern is the lack of information regarding changes in the variability of temperature and precipitation that would attend climate change. The lack of this information resulted in the formation of climate scenarios wherein the temporal variability of both precipitation and temperature were not changed (see Chapter 4: Methodology). This was considered a limitation or concern in many studies, some of which are discussed in this section.

In the Johnson et al. study on agricultural runoff and leaching (reviewed in Chapter 6: Agriculture), the results were considered to be limited by the failure to consider changes in storm frequency and duration that would result from climate change. The results of this study could be vastly different from those presented, depending upon assumptions concerning precipitation duration, frequency, and intensity, all of which would change if a changed daily variability were assumed.

Several studies on hydrology summarized in this report also are highly dependent upon assumptions about precipitation variability. These include the Lettenmaier et al. study on the hydrology of catchments in the Central Valley and the Sheer and Randall study on the impact of climate scenarios on water deliveries, both reviewed in Chapter 14: California. The scenarios assumed that the number of days of rainfall remains the same under the climate change. Model results in terms of predicting runoff amounts would be quite different if more rainfall events of lower intensity were assumed compared with the same number of rainfall events of (generally) higher intensity.

The studies for the Southeast (Chapter 16) did not consider changes in the frequency of droughts or severe storms such as hurricanes, which could certainly affect the likelihood of flooding for some coastal communities. However, these concerns are considered to be secondary to changes in sea level that would dominate in terms of changing the likelihood of floods.

Crop yields are very dependent on daily variability. For example, heat waves occurring during the grain filling process lower wheat yields. Whether a drought occurs early or late in the growing season has differential effects on yields. Changes in variability were not considered in the Rosenzweig, Peart et al., Ritchie, and Dudek studies (see Chapter 6: Agriculture).

Changes in the frequencies of extreme events are considered to be of great importance to potential forest disturbance, as discussed in Chapter 5: Forests. The possibility of increases in the frequencies of events such as droughts, flooding, wind, ice, or snowstorms may be of greater significance to forest survival than the gradual mean change in climate that has been studied so far.

The Kalkstein study, which is reviewed in Chapter 12: Human Health, is strongly dependent upon the determination of certain maximum temperature threshold values beyond which human mortality increases. In applying the death/weather effects statistical models to scenarios of climate change, Kalkstein held temperature variability constant, so that temperatures that exceed the threshold values are determined unrealistically.

Changes in the variability of temperature both seasonally and daily are important to studies concerned with the effect of temperature change on electricity demand (discussed in Chapter 10). Although new generating capacity requirements for the nation for 2010 and beyond are calculated assuming climate change, the numbers generated could be considerably different for any particular year, depending mainly on air-conditioning needs, which would be the major use increase for electricity. Such needs are sensitive to extremes in daily maximum temperatures and the persistence of such temperatures (i.e., heat waves).

It would be impossible to quantitatively or even qualitatively estimate how different the results of these studies would be if changes in climate variability had formed part of the climate scenarios made available as input for the various climate impact models used. Primarily, it is impossible because the variability changes are not known; second, it is impossible because most of the studies are so complex that the effect of a change in one variable (a complex change at that) is not intuitively obvious in most cases. Analyses of the sensitivity of the impact models involved to changes in variability would be required to provide specific answers. What can be said at this point is that the lack of information on climate variability has limited a number of studies in this report and has limited the completeness of the answers they could provide.

RESEARCH NEEDS

The research reported above clearly indicates that research of changes in climate variability associated with climate change is truly in its infancy. Much needs to be done. Future research needs may be broken into three categories: further analysis of GCMs; improvements in GCMs; and sensitivity analysis of impacts.

Further Investigation of Variability in GCMs

Results summarized here represent only an initial effort at looking at variability in GCMs. We need to examine in more models and at many more grid boxes the daily and interannual variability of many climate variables (such as relative humidity, solar radiation, and storm frequency) in addition to temperature and precipitation. Other time scales of variability also should be examined, such as 7- to 10-day scales, which correspond to the lifetime of many frontal storms. Moreover, the most sophisticated statistical techniques must be used or, where needed, developed, such that uniform quantitative indicators are available to evaluate both how well the current models reproduce present variability and how they forecast the change in variability under climate change conditions. The causes for discrepancies in present-day climate variability and control run variability must be better understood to attain a clearer understanding of future climate changes.

Improvements in GCMs

The results of Rind et al. and Mearns et al. give some indications that oversimplifications in the land surface packages of GCMs contribute to overpredictions of daily temperature variability. This possibility is further underlined by the better results obtained with Dickinson's model, which includes a more sophisticated land surface package. More detailed analyses of current GCMs are necessary to confirm this speculation, as well as to determine the causes of other errors in variability, such as for precipitation. Other known causes of error, such as the models' relative inability to investigated further. The next step involves altering the GCMs so that variability is properly simulated. Only then can much faith be put in GCM forecasts of variability changes with a perturbed climate.

Sensitivity Analyses of Impacts

It also must be determined how important changes in variability will be to different areas of impact. Since the variability of climate variables produced from GCMs cannot be "trusted" or even easily analyzed at this point, these sensitivity analyses of impact models should be performed with statistically simulated time series of climate variables, as has been performed by Schwarz (1976) and Mearns et al. (1984). By simulating time series, different levels of autocorrelation and variance in the time series may be controlled for and systematically varied. By this means, important thresholds of variability change for different variables as they affect the output of impact models can be determined. Moreover, ranges of possible impacts of variability change can be determined and can serve as guides until better information is available on how variability will change in a C02 warmed world.

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