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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

Editors: Joel B. Smith and Dennis Tirpak

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D: FORESTS

E: AQUATIC RESOURCES

F: AIR QUALITY

G: HEALTH

H: INFRASTRUCTURE

I: VARIABILITY

J: POLICY

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

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The following people contributed to this report:

Chapter 1: Introduction	Joel B. Smith
Chapter 2: Global Climate Change	Alan Robock
Chapter 3: Climate Variability	Linda O. Mearns
Chapter 4: Methodology	Joel B. Smith
Chapter 5: Forests	Jack K. Winjum Ronald P. Neilson
Chapter 6: Agriculture	Cynthia Rosenzweig Margaret M. Daniel
Chapter 7: Sea Level Rise	James G. Titus
Chapter 8: Biological Diversity	Lauretta M. Burke Ross A. Kiester
Chapter 9: Water Resources	Mark W. Mugler Michael C. Rubino
Chapter 10: Electricity Demand	Kenneth P. Linder
Chapter 11: Air Quality	Joseph J. Bufalini Peter L. Finkelstein Eugene C. Durman
Chapter 12: Human Health	Janice A. Longstreth
Chapter 13: Urban Infrastructure	Ted R. Miller
Chapter 14: California	George A. King Robert L. DeVelice Ronald P. Neilson Robert C. Worrest

Chapter 15: Great Lakes	Joel B. Smith
Chapter 16: Southeast	James G. Titus
Chapter 17: Great Plains	Cynthia Rosenzweig William E. Riebsame
Chapter 18: Research Needs	Anthony Janetos
Chapter 19: Preparing for Climate Change	James G. Titus

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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.

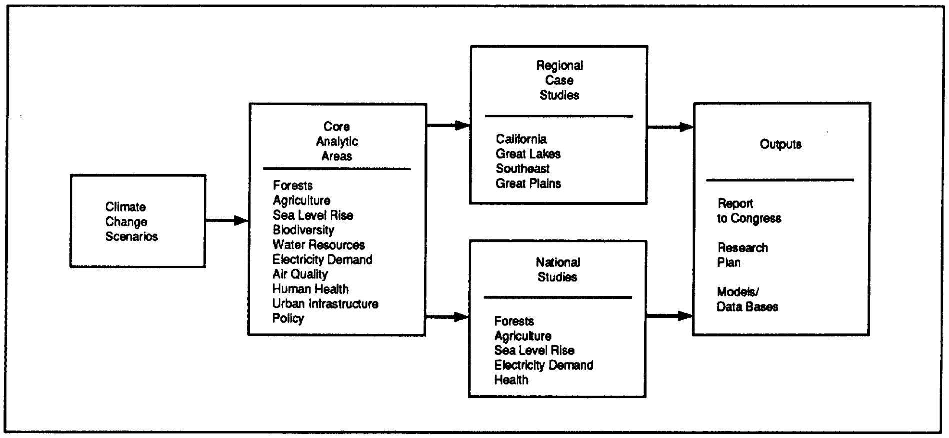


Figure 1. Elements of the effects report.

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

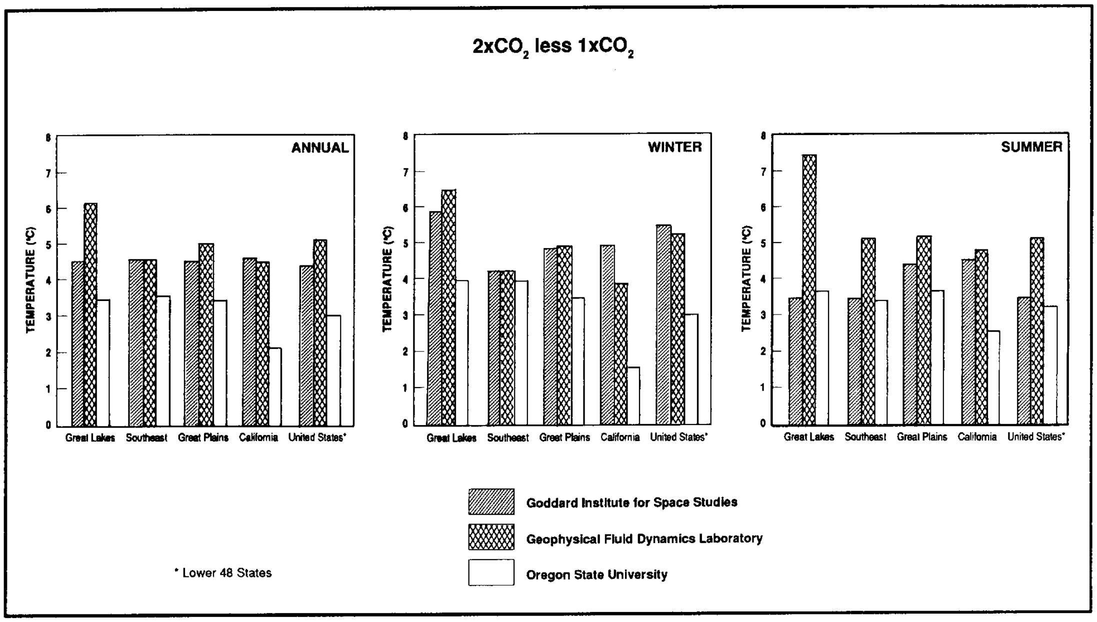


Figure 2. Temperature scenarios.

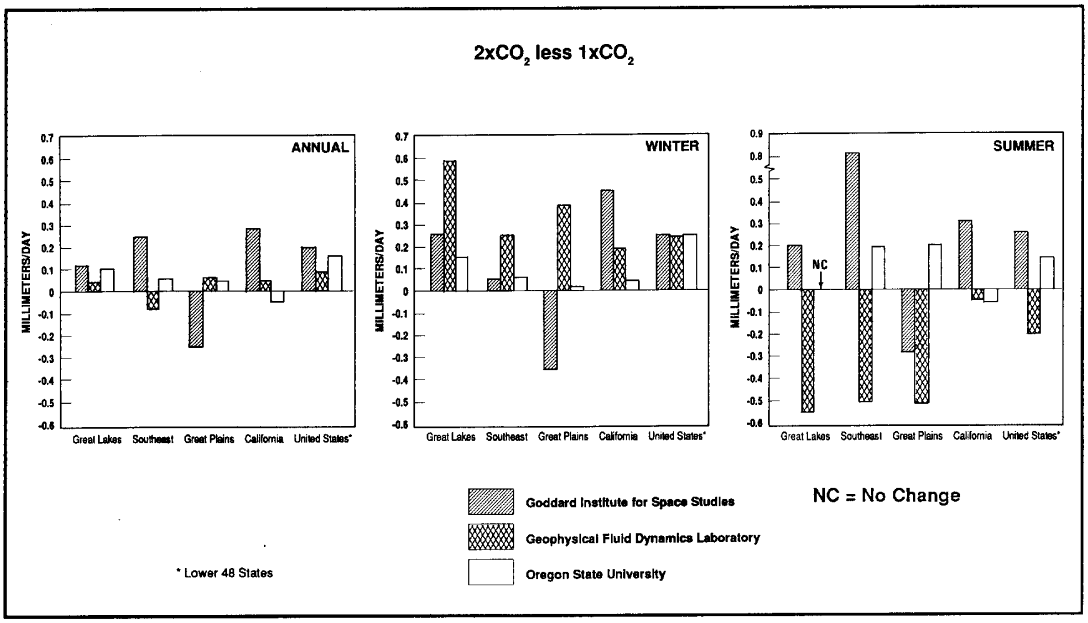


Figure 3. Precipitation scenarios

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

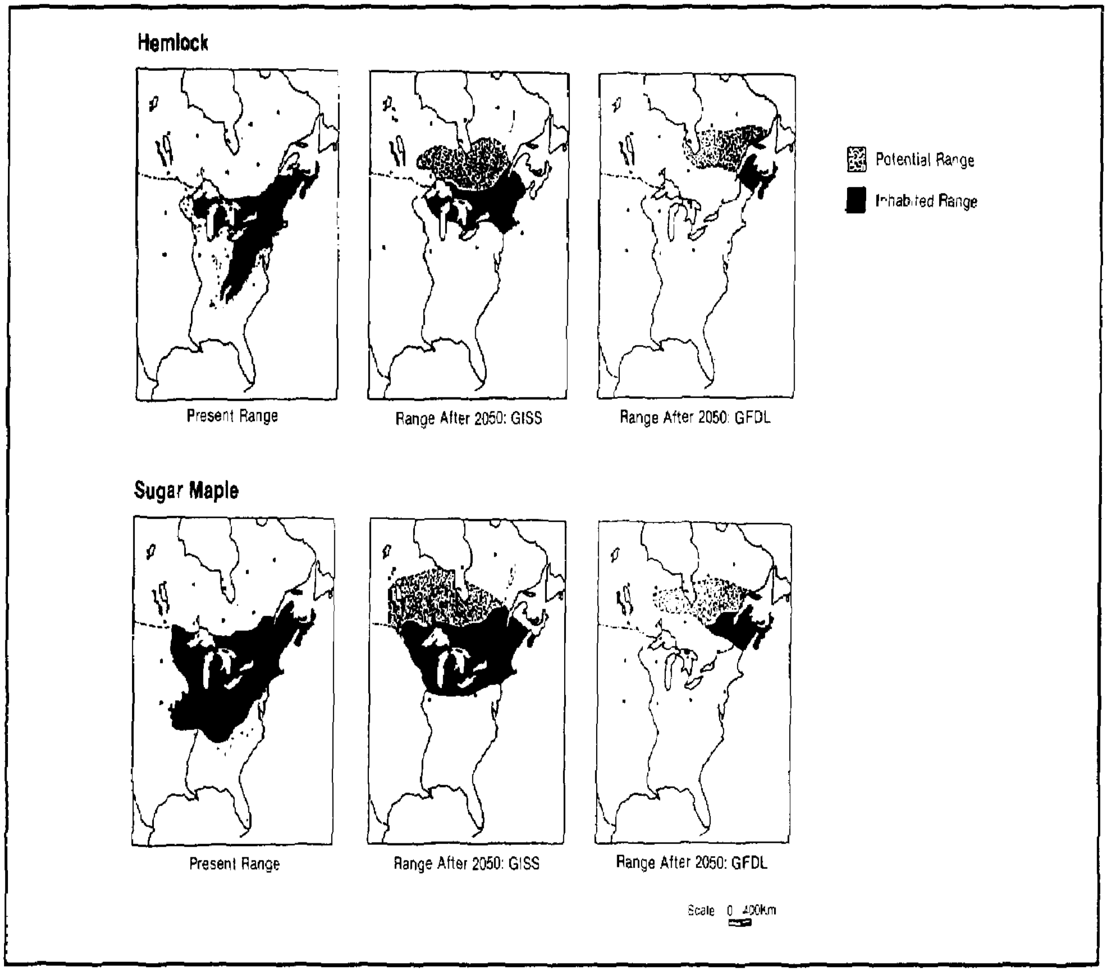


Figure 4. Shifts in range of hemlock and sugar maple under alternative climate scenarios.

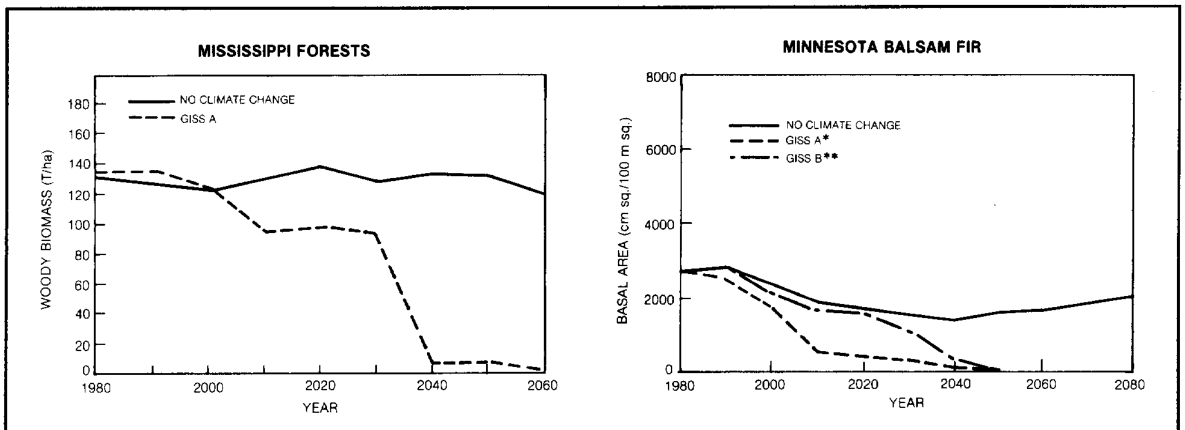
fast as the rate of migration of forests. Assuming a migration rate of 100 km (60 miles) per century, or double the known historic rate, the inhabited ranges of forests could be significantly reduced because the southern boundary may advance more quickly than the northern boundary. Even if climate stabilizes, 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.

<u>Protecting Developed Areas May Be Expensive</u>

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.

<u>Most Coastal Wetlands Would Be Lost</u>

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.

<u>Estuaries May Enlarge and Become More Saline</u>

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.

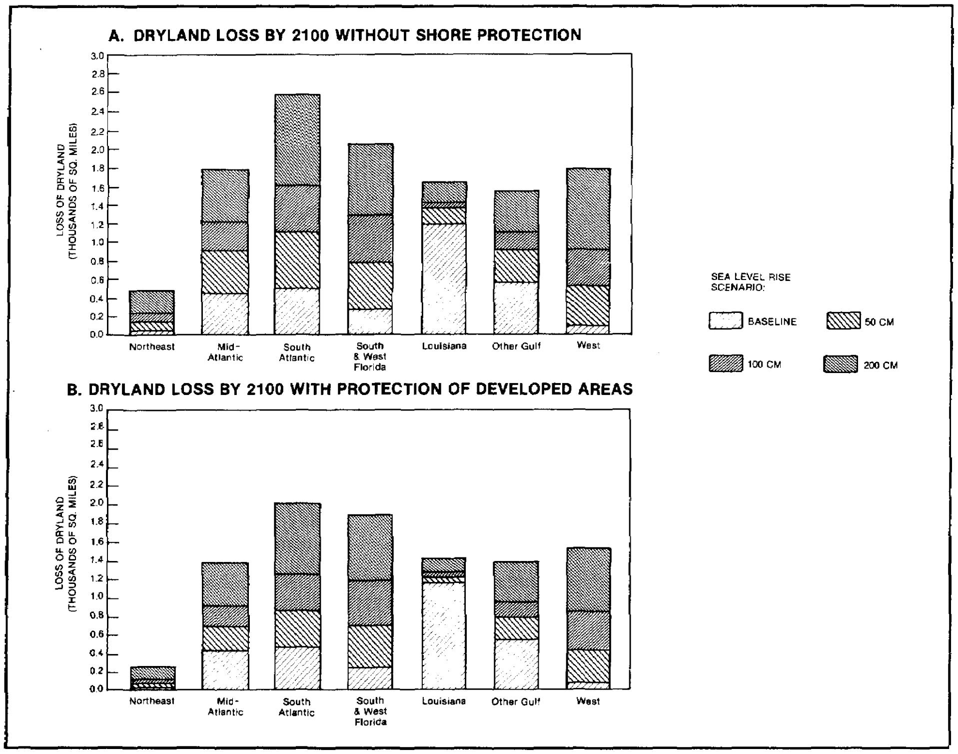


Figure 6. Dryland loss by 2100.

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

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 step up current efforts to combat salinity increases in surface water and groundwater supplies.

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%.

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 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 were estimated for California using a simple agroclimatic index. The studies did not examine effects on yields of introduction of crops, such as citrus, into new areas; changes in weed growth caused by higher CO_2 concentrations; or new technologies, such as biotechnology. Some of these changes could enhance the ability of agriculture to adapt to global warming.

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

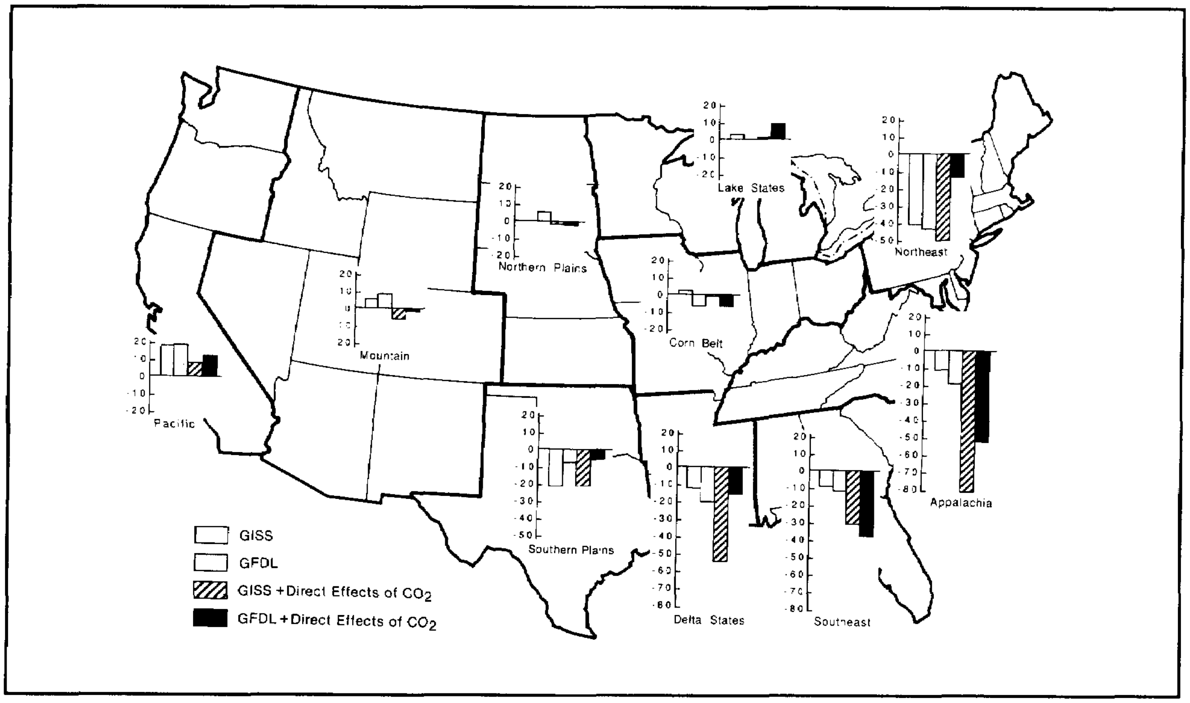


Figure 7. Percent change in regional agricultural acreage.

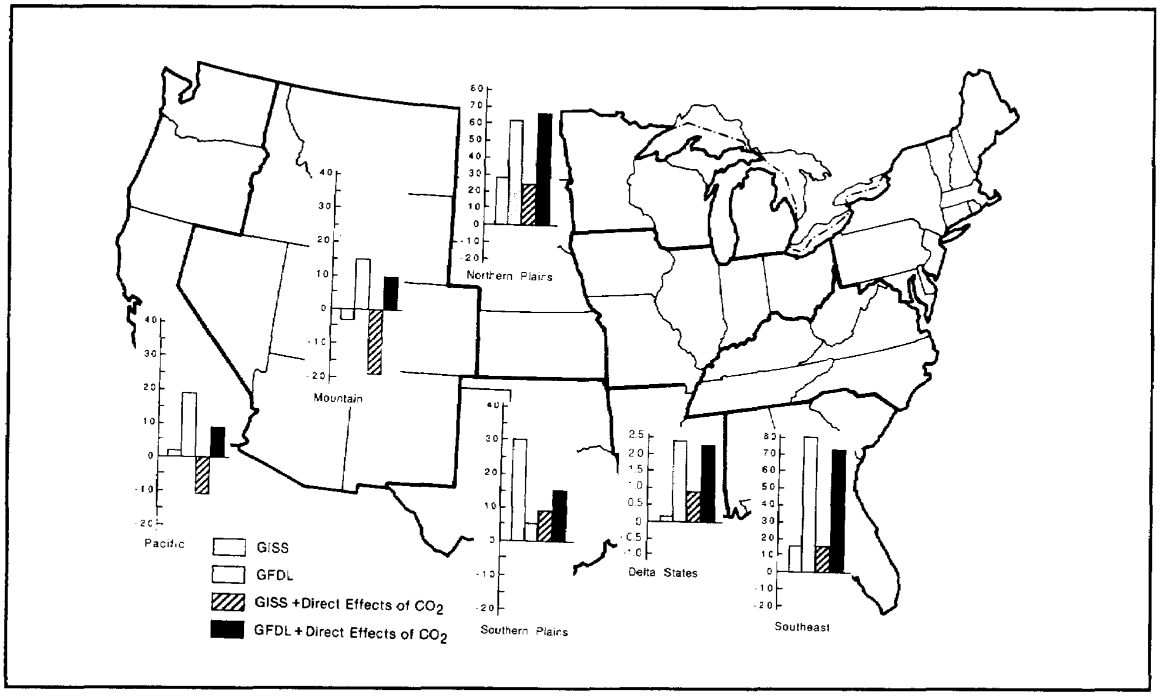


Figure 8. Change in regional irrigation acreage (100,000 of acres).

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

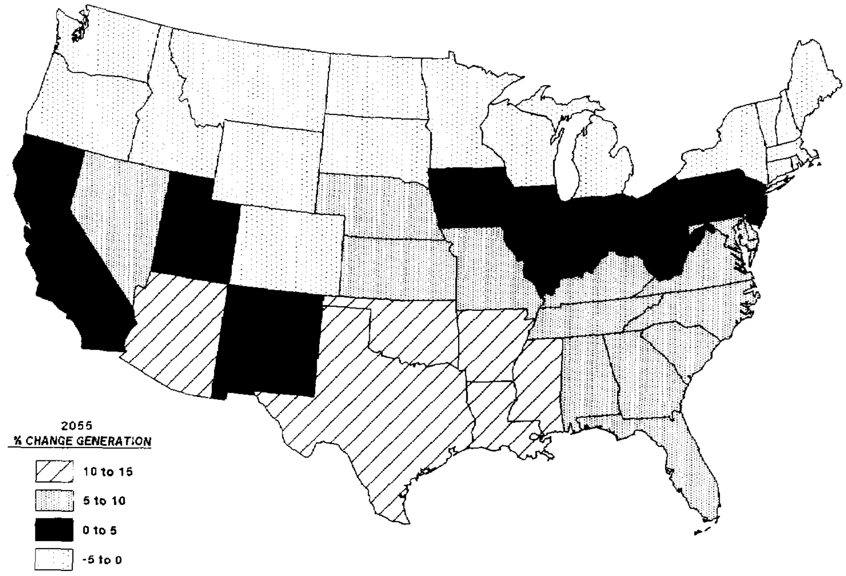


Figure 9. Changes in electricity generation by state, induced by climate change scenarios by 2055.

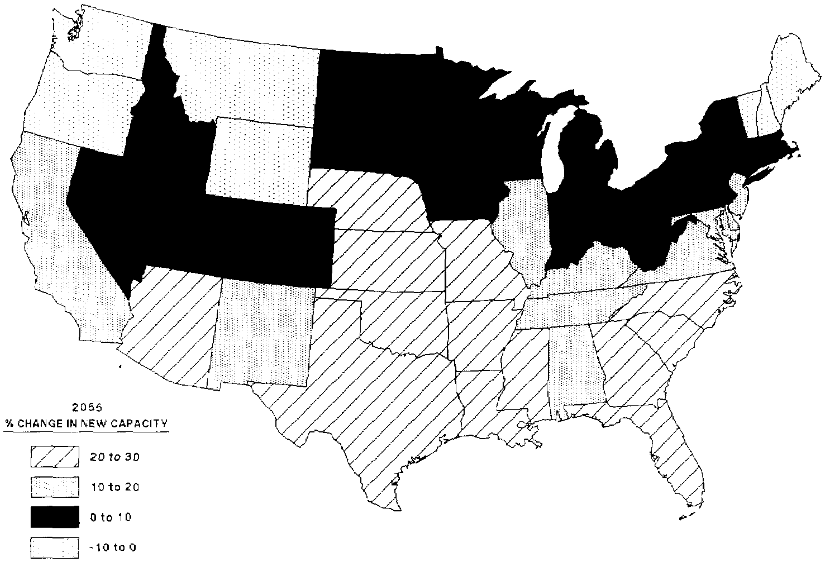


Figure 10. Changes in electricity capacity by state, induced by climate change scenarios in 2055.

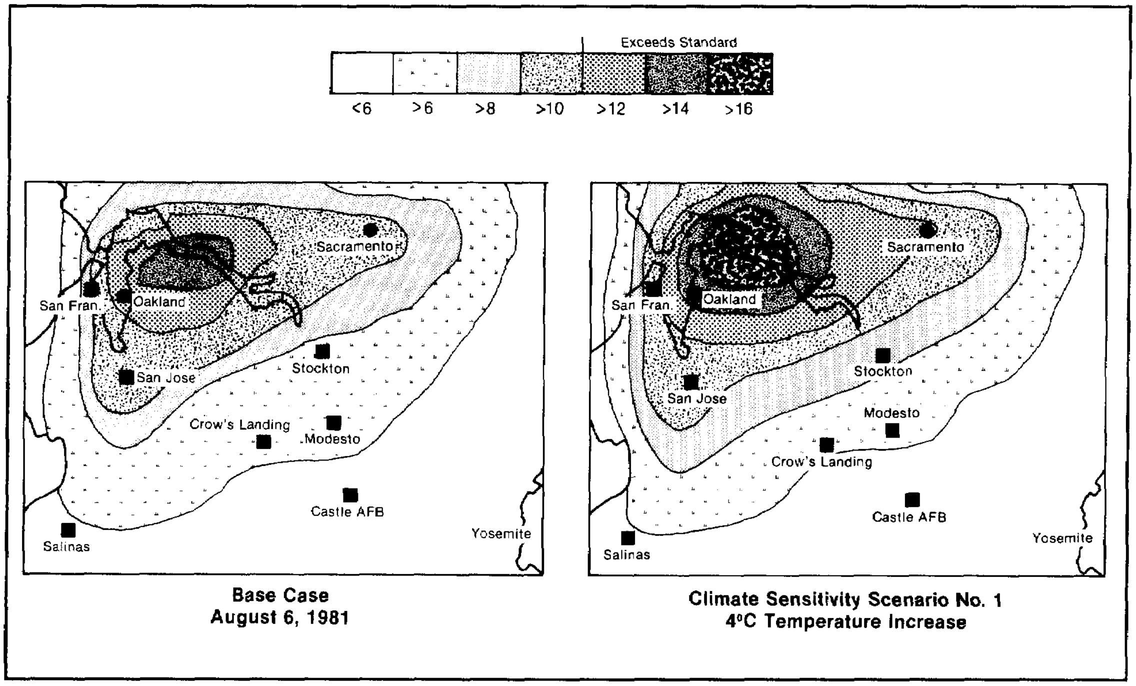
several regions. The latter analysis did not consider reduction in emissions of air pollutants due to enforcement of the Clean Air Act.

Climate Changes Could Increase Air Pollution, Especially Smog

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

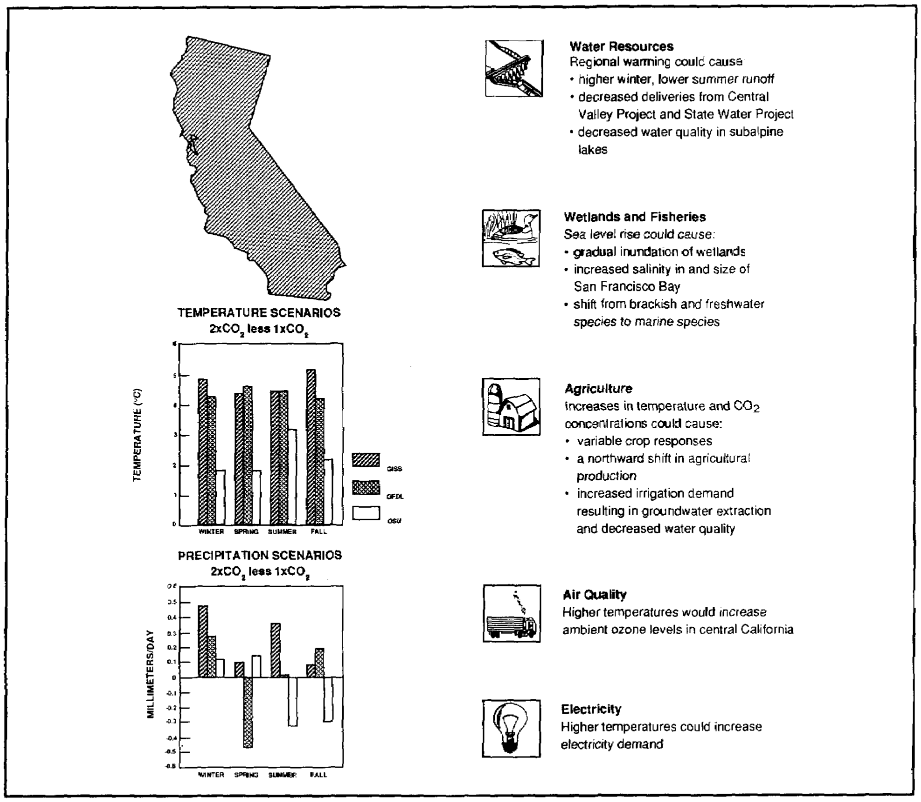
Warmer temperatures would change the seasonality of runoff from the mountains surrounding the Central Valley. Runoff would be higher in the winter months as a result of less snowpack and more precipitation in the form of rain. Consequently, runoff would be lower in the late spring and summer. Under these 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.



Water Resources
Regional warming could cause
- higher winter, lower summer runoff
- decreased deliveries from Central Valley Project and State Water Project
- decreased water quality in subalpine lakes

Wetlands and Fisheries
Sea level rise could cause:
- gradual inundation of wetlands
- increased salinity in and size of San Francisco Bay
- shift from brackish and freshwater species to marine species

Agriculture
Increases in temperature and CO_2 concentrations could cause:
- variable crop responses
- a northward shift in agricultural production
- increased irrigation demand resulting in groundwater extraction and decreased water quality

Air Quality
Higher temperatures would increase ambient ozone levels in central California

Electricity
Higher temperatures could increase electricity demand

Figure 12. California

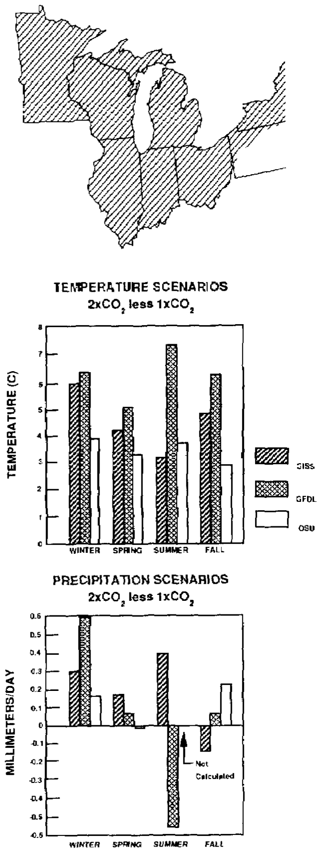
Climate Change Could Degrade Air Quality in California

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 CO_2
- 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.

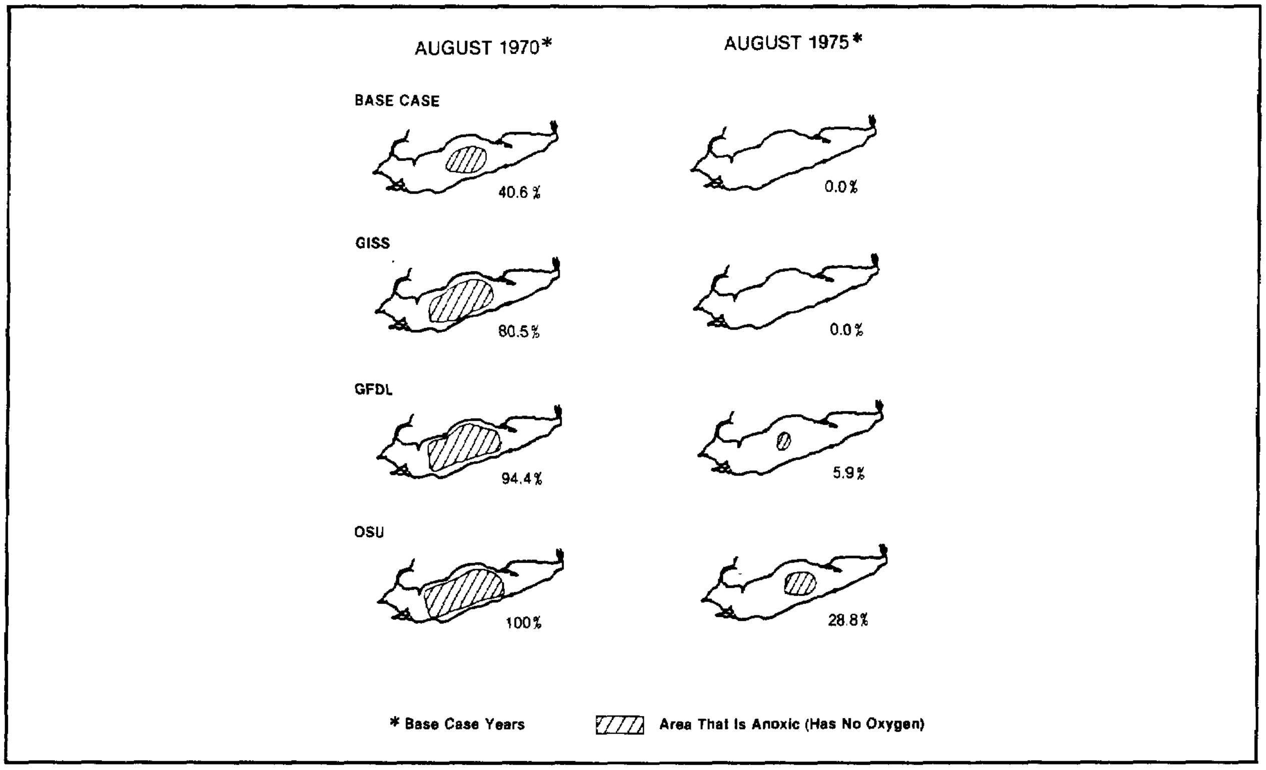


Figure 14. Area of central basin of Lake Erie that becomes anoxic under doubled CO_2 scenarios.

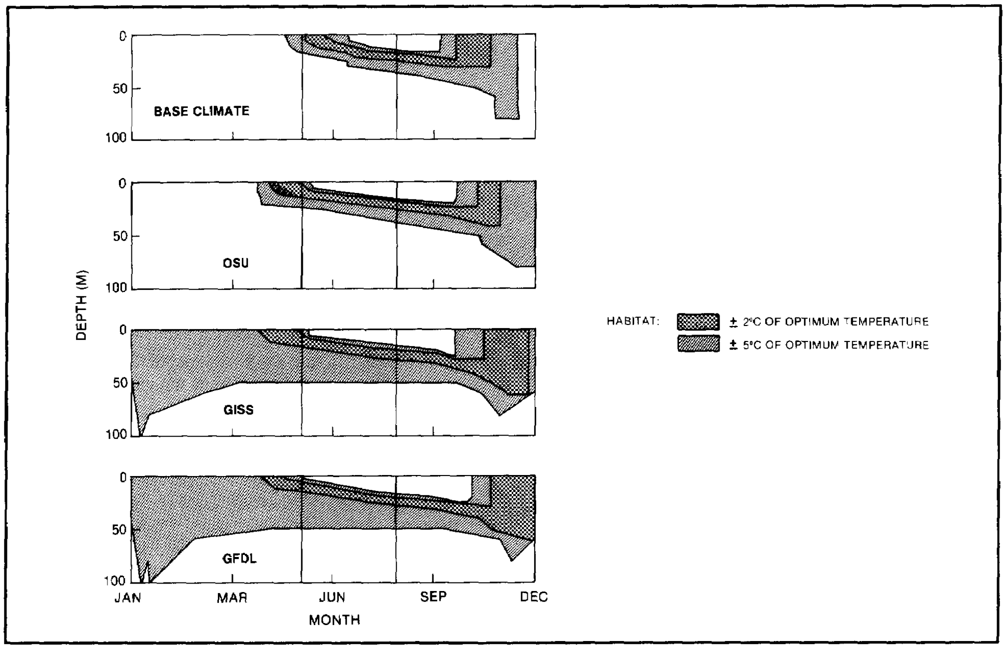


Figure 15. Increases in thermal habitat for lake trout in southern Lake Michigan under alternative climate scenarios.

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.

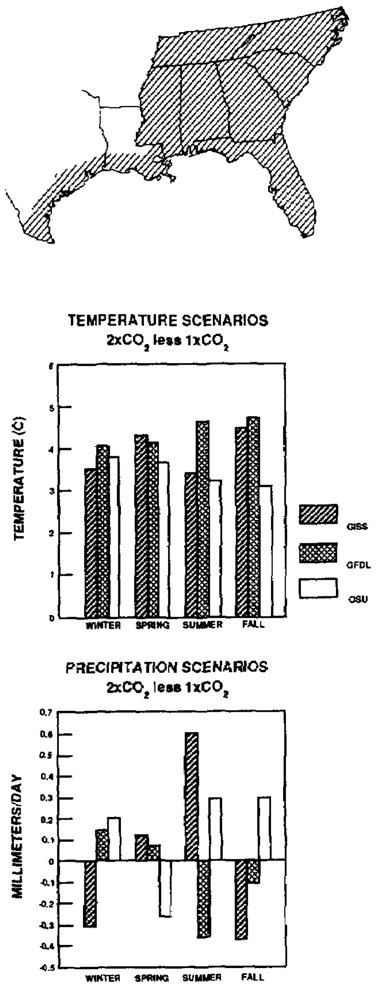
Southeast

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

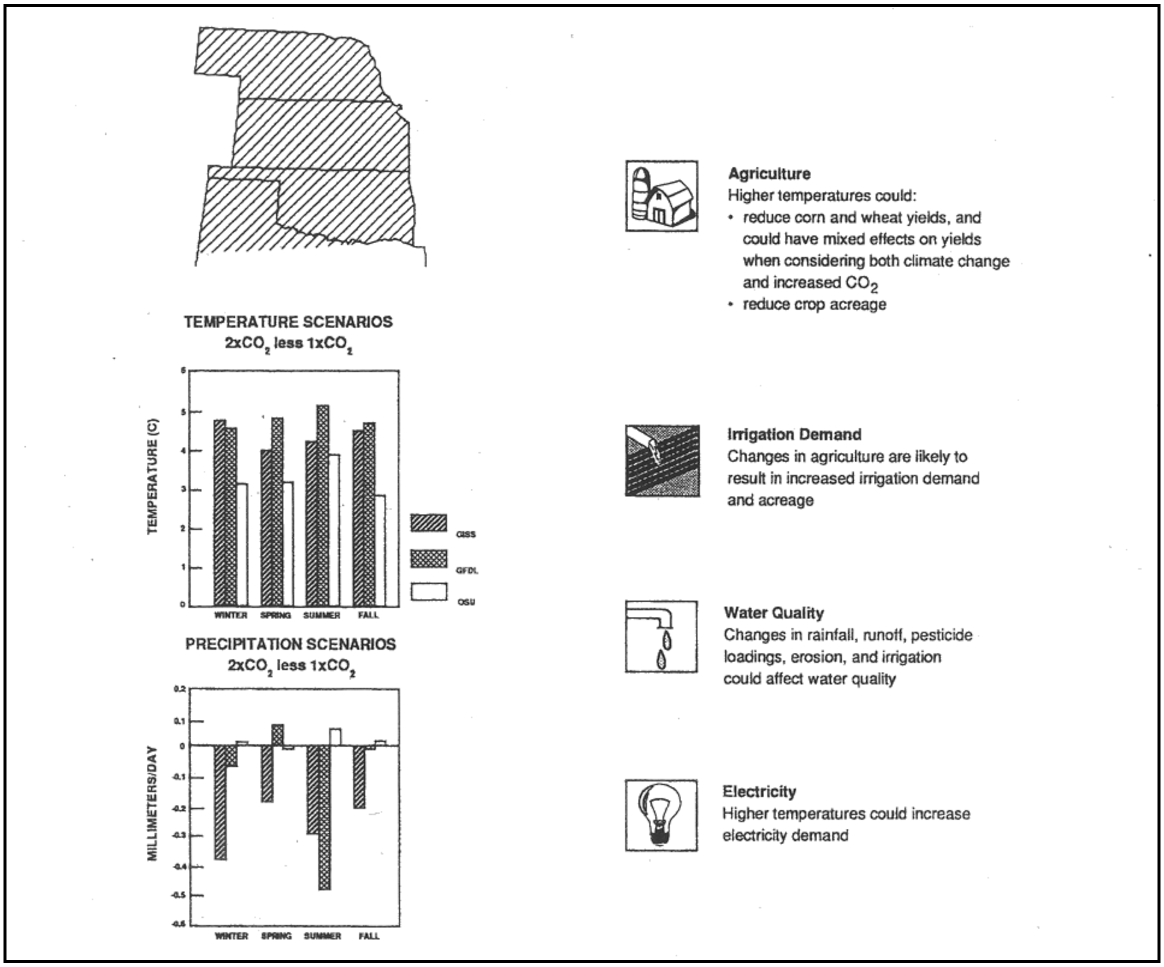
The crop yield and economic adjustment studies indicate that grain crop acreage could diminish in the region. The direction of changes in wheat and corn yields depends on the direct effects of CO_2 on crop growth and the severity of climate change. If climate becomes hotter and relatively drier, yields 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?

CHAPTER 1
INTRODUCTION

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

<u>Since the rate and extent of climate change on a red level are uncertain, we cannot predict effects</u>. 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.

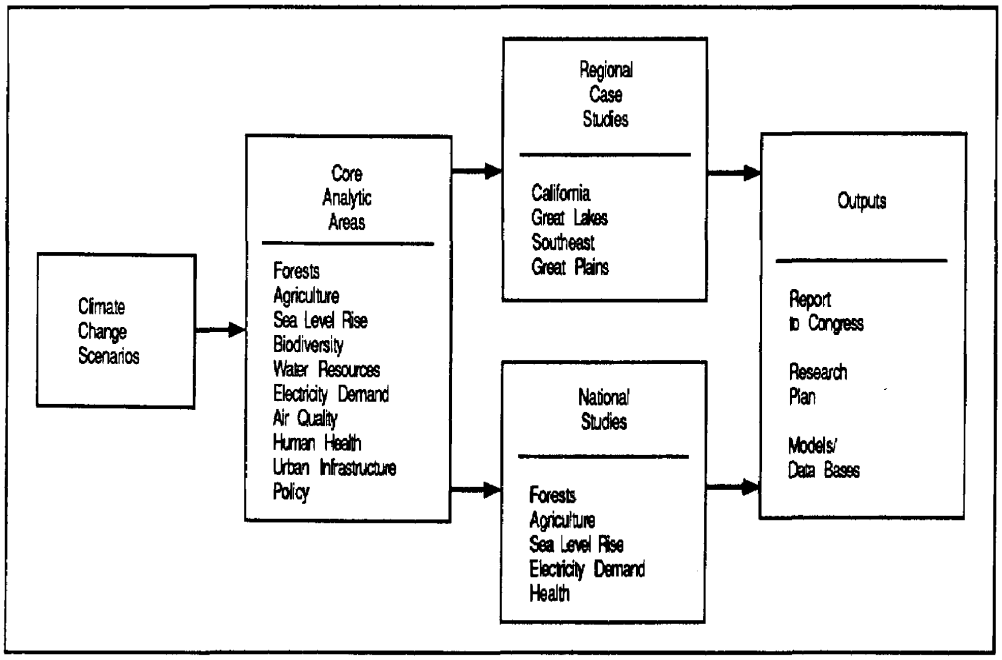


Figure 1-1. Elements of the effects report.

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.

REFERENCES

National Academy of Sciences. 1979. Carbon Dioxide and Climate: A Scientific Assessment. Washington, DC: National Academy Press.

National Academy of Sciences. 1983. Changing Climate. Washington, DC: National Academy Press.

National Academy of Sciences. 1987. Current Issues in Atmospheric Change. Washington, DC: National Academy Press.

Scope 29. 1986. The Greenhouse Effect, Climatic Change, and Ecosystems (SCOPE 29). Bolin, B., B. Doos, J. Hager, and R. Warrick (eds). Chichester, England: John Wiley and Sons.

United Nations Environment Programme. 1986. Effects of Changes in Stratospheric Ozone and Global Climate. Titus, J.G. (ed). Washington, DC: U.S. EPA and United Nations Environment Programme.

U.S. Department of Energy. 1985a. Atmospheric Carbon Dioxide and the Global Carbon Cycle. Trabalka, J.R. (ed). Washington, DC: Government Printing Office (DOE/ER-0239).

U.S. Department of Energy. 1985b. Projecting the Climatic Effects of Increasing Carbon Dioxide. MacCracken, M.C., and F.M. Luther (eds). Washington, DC: Government Printing Office (DOE/ER-0237).

World Meteorological Organization. 1986. Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, Villach, Austria, 9-15 October 1985. World Climate Programme Report No. 661. Geneve, Switzerland: World Meteorological Organization, The International Council of Scientific Unions, and the United Nations Environment Programme.

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CHAPTER 2
GLOBAL CLIMATE CHANGE

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.

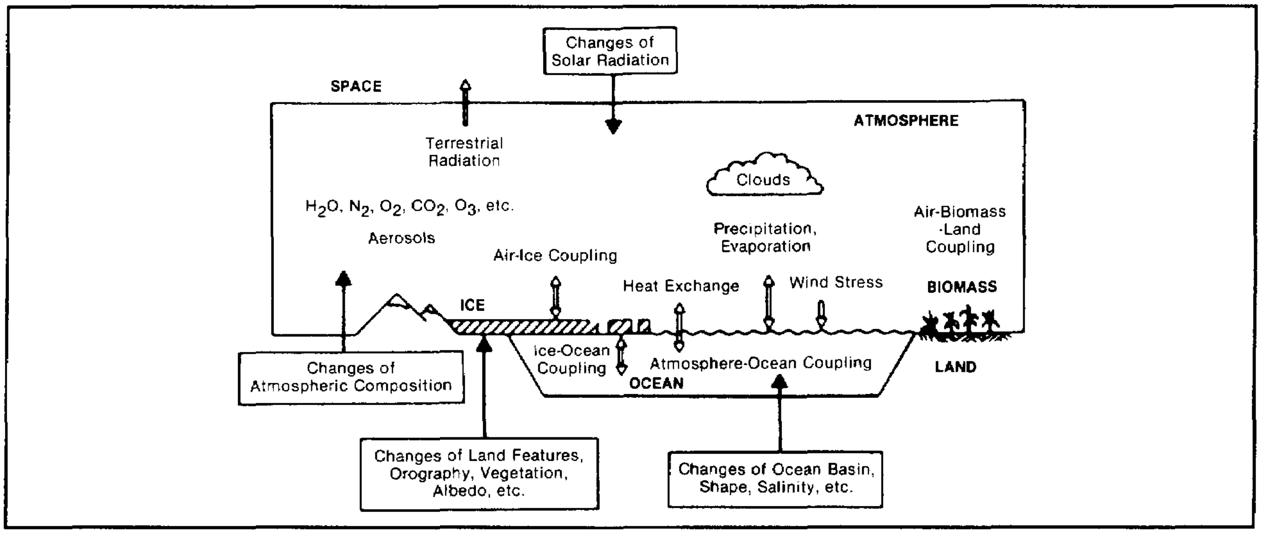


Figure 2-1. The climate system. The principal interactions among components of the atmosphere, ocean, ice, and land surface, and some examples of external forcings are indicated (Gates, 1979).

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.

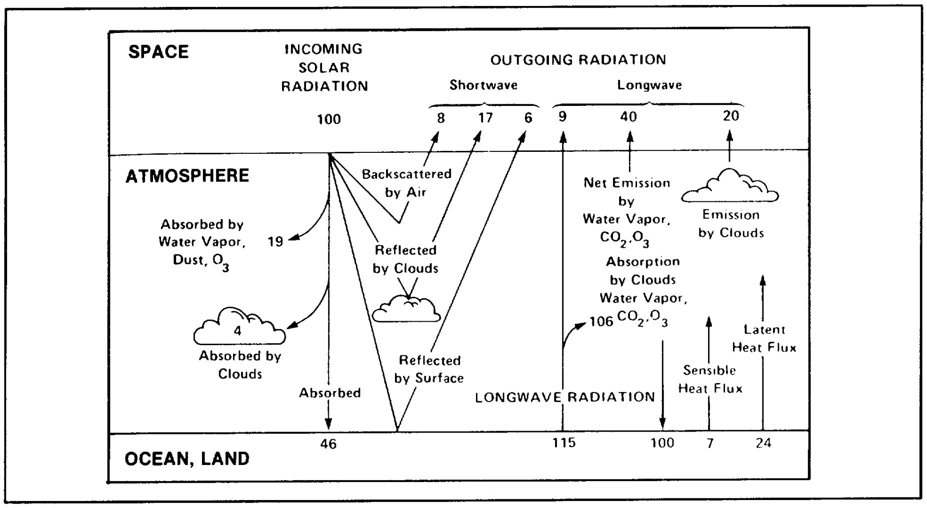


Figure 2-2. The Earth's energy balance. If the average amount of solar radiation received by the Earth (342 watts per meter2) is represented as 100 units, then the amplitudes of the various components of the energy flux are shown proportionately (MacCracken, 1985).

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.

<u>Chlorofluorocarbons (CFCs)</u>

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.

<u>Nitrous Oxide (N_2O)</u>

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.

<u>Ozone (O_3)</u>

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.

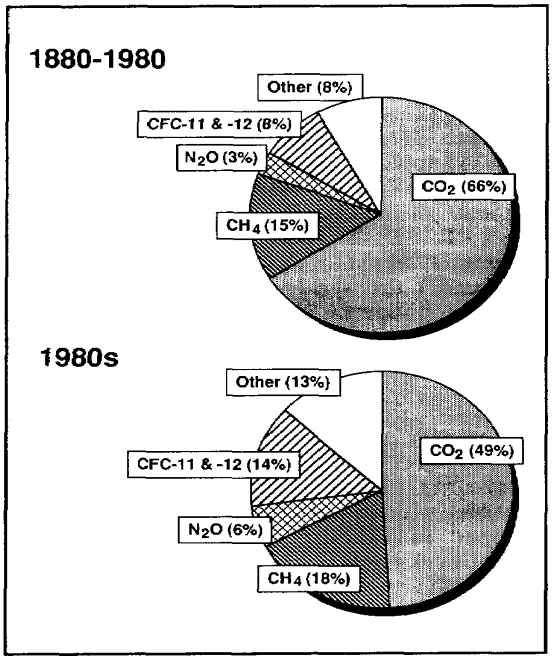


Figure 2-4. Greenhouse gas contributions to global warming; estimated values based on concentration changes (1880-1980: Ramanathan et al., 1985; 1985, 1980s: Hansen et al., 1988).

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.

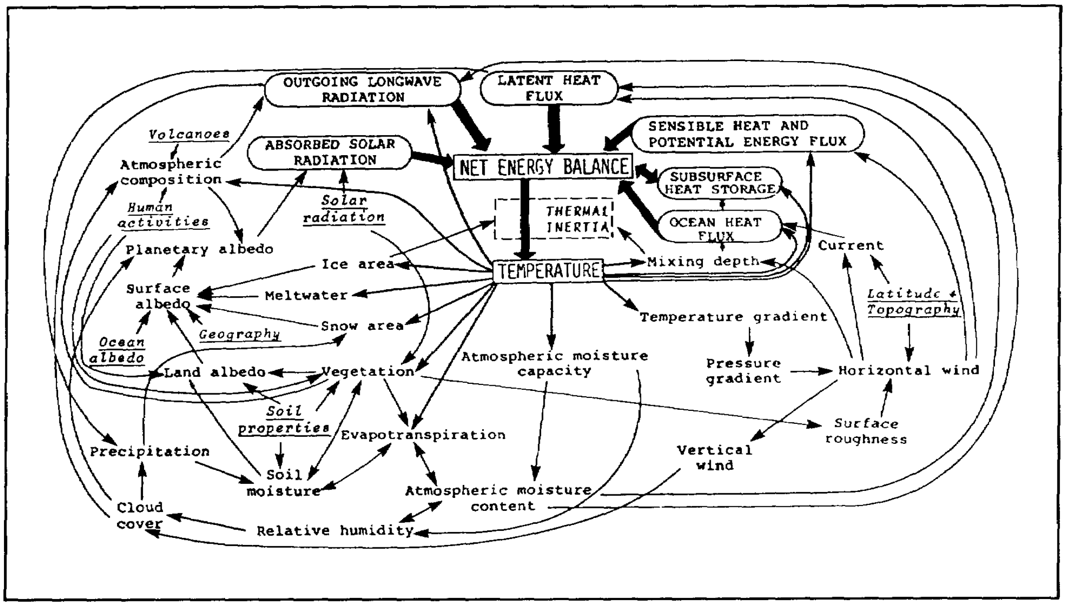


Figure 2-5. Physical climate feedback relationships. External forcings are indicated in underlined italics (Robock, 1985).

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

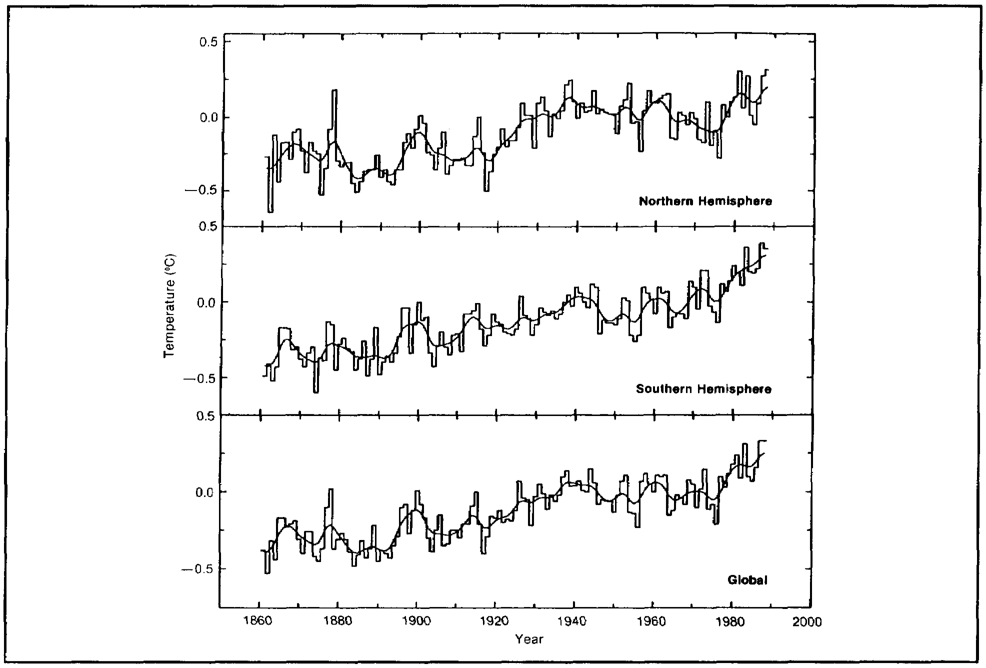


Figure 2-6. Hemispheric and global surface air temperatures, 1861-1988. The 1988 value is preliminary and includes data only through November. This record incorporates measurements made both over land and from ships. The smooth curve shows 10-year Gaussian filtered values. The gradual warming during 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).

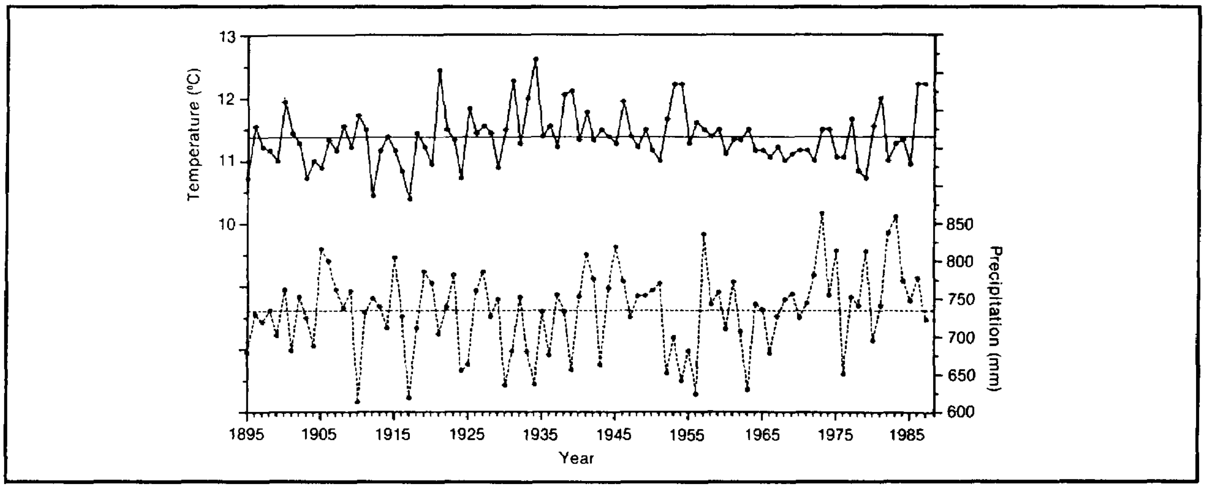


Figure 2-7. Annual average surface air temperature (solid) and precipitation for the contiguous United States, 1895-1987. Note that the United States has been cooling for the past 50 years (Hansen et al., 1988).

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.

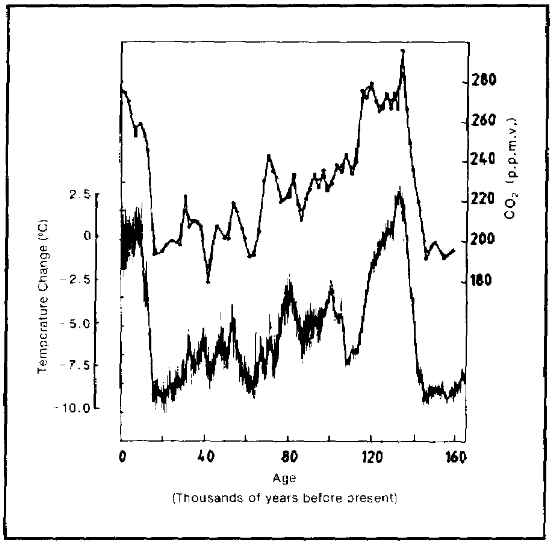


Figure 2-8. Temperatures and carbon dioxide concentrations for the past 160,000 years at Vostok, Antarctica. Since these observations were taken near the South Pole, they show larger temperature variations (by a factor of 2 or 3) than took place averaged over the whole globe (Barnola et al., 1987).

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.

REFERENCES

Angell, J.K. 1988. Impact of El Niño on the delineation of tropospheric cooling due to volcanic eruptions. Journal of Geophysical Research 93:3697-3704.

Barnett, T.P. 1985. On long-term climate change in observed physical properties of the ocean. In: MacCracken, M.C., and F.M. Luther, eds.

Detecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy, (DOE/ER-0235), pp. 91-107.

Barnola, J.M., D. Raynaud, Y.S. Korotkevich, and C. Lorius. 1987. Vostok ice core provides 160,000-year record of atmospheric CO_2. Nature 329:408-414.

Blake, D.R., and F.S. Rowland. 1988. Continuing worldwide increase in tropospheric methane, 1978-1987. Science 239:1129-1131.

Broecker, W. 1987. Unpleasant surprises in the greenhouse? Nature 328:123-126.

Charlson, R., J. Lovelock, M. Andreae, and S. Warren. 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. Nature 326:655-661.

Dickinson, R.E. 1984. Modeling evapotranspiration for three-dimensional global climate models. In: Hansen, J.E., and T. Takahashi, eds. Climate Processes and Climate Sensitivity. Washington, DC: American Geophysical Union, pp. 58-72.

Dickinson, R.E. 1986. The climate system and the modelling of future climate. In: Bolin, B., B. Doos, J. Hager, and R. Warrick, eds. The Greenhouse Effect, Climatic Change, and Ecosystems (SCOPE 29). Chichester, England: John Wiley and Sons, pp. 207-270.

Gates, W.L. 1979. The physical basis of climate. In: Proceedings of the World Climate Conference. WMO No. 421. Geneva, Switzerland: World Meteorological Organization, pp. 112-131.

Grotch, S.L. 1988. Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data. Washington, DC: U.S. Department of Energy. (DOE/NBB-0084).

Hansen, J., I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, and G. Russell. 1988. Global climate changes as forecast by the GISS 3-D model. Journal of Geophysical Research 93:9341-9364.

Hansen, J., and S. Lebedeff. 1988. Global surface air temperatures: update through 1987. Geophysical Research Letters 15:323-326.

Hansen, J., G. Russell, A. Lacis, I. Fung, and D. Rind. 1985. Climate response times: Dependence on climate sensitivity and ocean mixing. Science 229:857-859.

Hansen, J.E., W.C. Wang, and AA. Lacis. 1978. Mount Agung eruption provides test of a global climatic perturbation. Science 199:1065-1068.

Hansen, K., GA. Maul, and T.R. Karl. 1989. Are atmospheric "greenhouse" effects apparent in the climatic record of the contiguous U.S. (1895-1987)? Geophysical Research Letters 16:49-52.

Hasselinann, K. 1976. I. Stochastic climate models. Theory. Tellus 28:473-485.

Karl, T.R., H. Diaz, and T. Barnett. 1989. Climate variations of the past century and the greenhouse effect (A report based on the First Climate Trends Workshop). Rockville, MD: National Climate Program Office/NOAA.

Keeling, C.D. 1984. The global carbon cycle: What we know and could know from atmospheric, biospheric, and oceanic observations. In: Institute for Energy Analysis. Proceedings: Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus. Washington, DC: U.S. Department of Energy, (DOE CONF-820970).

Khalil, MAX, and RA. Rasmussen. 1987. Nitrous oxide: Trends and global mass balance over the last 3,000 years. Annals of Glaciology 10:73-79.

Lashof, D. 1989. The dynamic greenhouse: Feedback processes that may influence future concentrations of greenhouse gases. Climatic Change.

Lashof, D., and D. Tirpak, eds. 1989. U.S. Environmental Protection Agency. Policy Options for Stabilizing Global Climate. Draft Report to Congress. Washington, DC: U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation.

February.

Lorenz, E.N. 1968. Climatic determinism. Meteorological Monographs 30:1-30.

MacCracken, M.C. 1985. Carbon dioxide and climate change: Background and overview. In: MacCracken, M.C., and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy, (DOE/ER-0237), pp. 1-23.

MacCracken, M.C., and F.M. Luther, eds. 1985a. Projecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy. (DOE/ER-0237).

MacCracken, M.C., and F.M. Luther, eds. 1985b. Detecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy. (DOE/ER-0235).

Manabe, S., and R.J. Stouffer. 1980. Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. Journal of Geophysical Research 85:5529-5554.

National Research Council. 1979. Carbon Dioxide and Climate: A Scientific Assessment. Washington, DC: National Academy Press.

National Research Council. 1983. Changing Climate. Washington, DC: National Academy Press.

National Research Council. 1985. Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change. Washington, DC. U.S. Department of Energy. (DOE/EV/60235-1).

National Research Council. 1987. Current Issues in Atmospheric Change. Washington, DC: National Academy Press.

Neftel, A., E. Moor, H. Oeschger, and B. Stauffer. 1985. Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries. Nature 315:45-47.

Pearman, G.I., D. Etheridge, F. deSilva, and P.J. Fraser. 1986. Evidence of changing concentrations of atmospheric CO_2, N_2O, and CH_4 from air bubbles in Antarctic ice. Nature 320:2448-250.

Ramanathan, V. 1988. The greenhouse theory of climate change: A test by an inadvertent global experiment. Science 240:293-299.

Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann. 1989. Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. Science 243:57-63.

Ramanathan, V., RJ. Cicerone, H.B. Singh, and J.T. Kiehl. 1985. Trace gas trends and their potential role in climate change. Journal of Geophysical Research 90:5557-5566.

Raynaud, D., J. Chappellaz, J.M. Barnola, Y.S. Korotkevich, and C. Lorious. 1988. Climatic and CH_4 cycle implications of glacial-interglacial CH_4 change in the Vostok ice core. Nature 333:655-657.

Robock, A. 1978. Internally and externally caused climate change. Journal of the Atmospheric Sciences 35:1111-1122.

Robock, A. 1979. The "Little Ice Age": Northern Hemisphere average observations and model calculations. Science 206:1402-1404.

Robock, A. 1981. A latitudinally dependent volcanic dust veil index, and its effect on climate simulations. Journal of Volcanology and Geothermal Research 11:67-80.

Robock, A. 1983. Ice and snow feedbacks and the latitudinal and seasonal distribution of climate sensitivity. Journal of the Atmospheric Sciences 40:986-997.

Robock, A. 1984. Climate model simulations of the effects of the El Chichón eruption. Geofssíca Internacional 23:403-414.

Robock, A. 1985. An updated climate feedback diagram. Bulletin of the American Meteorological Society 66:786-787.

Schlesinger, M.E. 1985. Analysis of results from energy balance and radiative-convective models. In: MacCracken, M.C., and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy, (DOE/ER-0237), pp. 280-319.

Schlesinger, M.E. 1988. How to make models for behaviour of clouds. Nature 336:315-316.

Schlesinger, M.E., and J.F.B. Mitchell. 1985. Model projections of the equilibrium climatic response to increased carbon dioxide. In: MacCracken, M.C., and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy, (DOE/ER-0237), pp. 81-147.

Sellers, PJ., Y. Mintz, Y.C. Sud, and A. Dalcher. 1986. A simple biosphere model (SiB) for use within general circulation models. Journal of the Atmospheric Sciences 43:SOS-S31.

Somerville, R.C.J., and LA. Remer. 1984. Cloud optical thickness feedbacks in the CO climate problem. Journal of Geophysical Research 89:9668-9672.

Stauffer, B., G. Fischer, A. Neftel, and H. Oeschger. 1985. Increase of atmospheric methane recorded in Antarctic ice cores. Science 229:1386-1389.

Stauffer, B., E. Lochbronner, H. Oeschger, and J. Schwander. 1988. Methane concentration in the glacial atmosphere was only half that of the preindustrial Holocene. Nature 332:812-814.

Strain, B.R., and J.D. Cure, eds. 1985. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. (DOE/ER-0238).

Trabalka, J.R., ed. 1985. Atmospheric Carbon Dioxide and the Global Carbon Cycle. Washington, DC: U.S. Department of Energy. (DOE/ER-0239).

Trenberth, K.E., G.W. Branstator, and P.A. Arkin. 1988. Origins of the 1988 North American drought. Science 242:1640-1645.

Vinnikov, K.Ya., P.Ya. Groisman, K.M. Lugina, and A.A. Golubev. 1987. Variations in Northern Hemisphere mean surface air temperature over 1841-1985. Meteorology and Hydrology No. 1: 45-55. In Russian.

White, M.R., ed. 1985. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. (DOE/ER-0239).

Wigley, T.M.L., P.D. Jones, and P.M. Kelly. 1986. Empirical climate studies. In: Bolin, B., B. Doos, J. Hager, and R. Warrick, eds. The Greenhouse Effect, Climatic Change, and Ecosystems (SCOPE 29). Chichester, England: John Wiley and Sons, pp. 271-322.

Wigley, T.M.L., P.D. Jones, P.M. Kelly, and S.C.B. Raper. 1989. Statistical significance of global warming. Proceedings of the Thirteenth Annual Climate Diagnostics Workshop. Washington, DC: National Oceanographic and Atmospheric Administration. pp. A-1 -A-8.

Wigley, T.M.L., and S.C.B. Raper. 1987. Thermal expansion of sea water associated with global warming. Nature 330:127-131.

Wigley, T.M.L., and M.E. Schlesinger. 1985. Analytical solution for the effect of increasing CO_2 on global mean temperature. Nature 315:649-652.

Willson, R.C., and H.S. Hudson. 1988. Solar luminosity variations in solar cycle 21. Nature 332:810-812.

World Meteorological Organization. 1986a. Atmospheric Ozone 1985. Assessment of Our Understanding of the Processes Controlling Its Present Distribution and Change. Global Ozone Research and Monitoring Project - Report No. 16. Geneva, Switzerland: World Meteorological Organization.

World Meteorological Organization. 1986b. Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, Villach, Austria, 9-15 October 1985. World Climate Programme Report No. 661. Geneva, Switzerland: World Meteorological Organization.

CHAPTER 3
VARIABILITY

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.

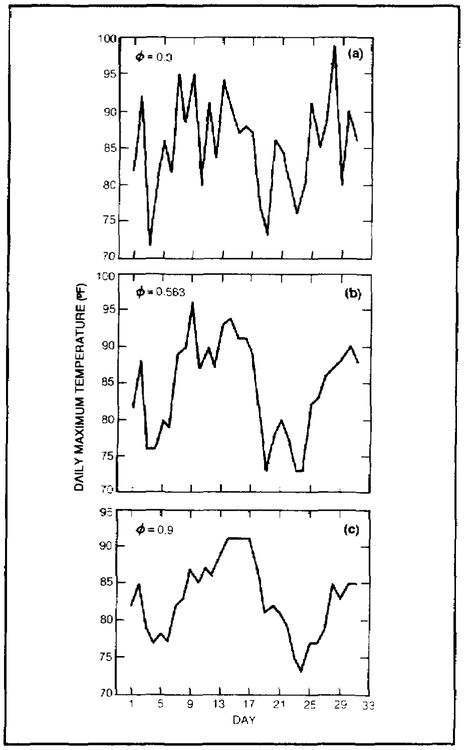
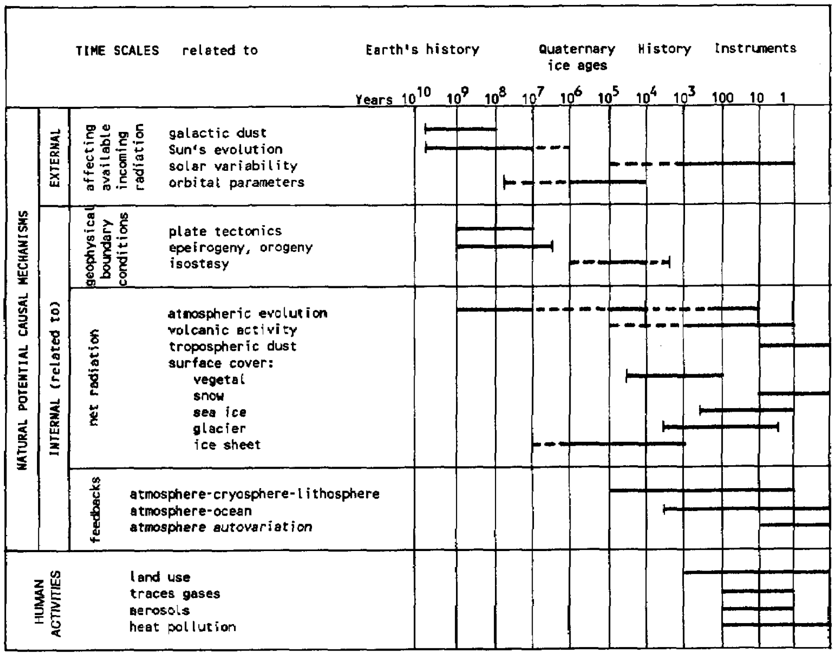


Figure 3-1. Simulated July daily maximum temperature time series at Des Moines, Iowa. All assume the same average temperature but use different statistical estimates (first-order autocorrelation coefficient 0) of variability (Mearns et al., 1984).

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

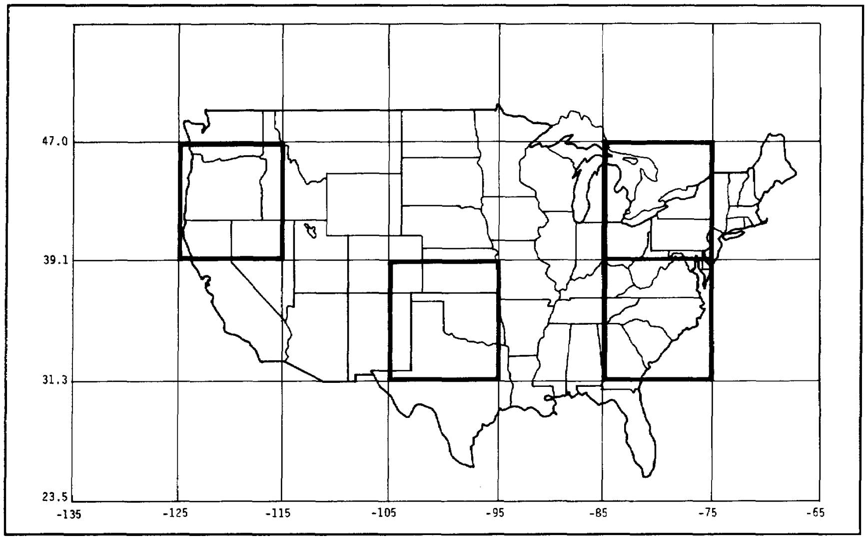

Figure 3-2. The locations of the four GISS model grids.

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

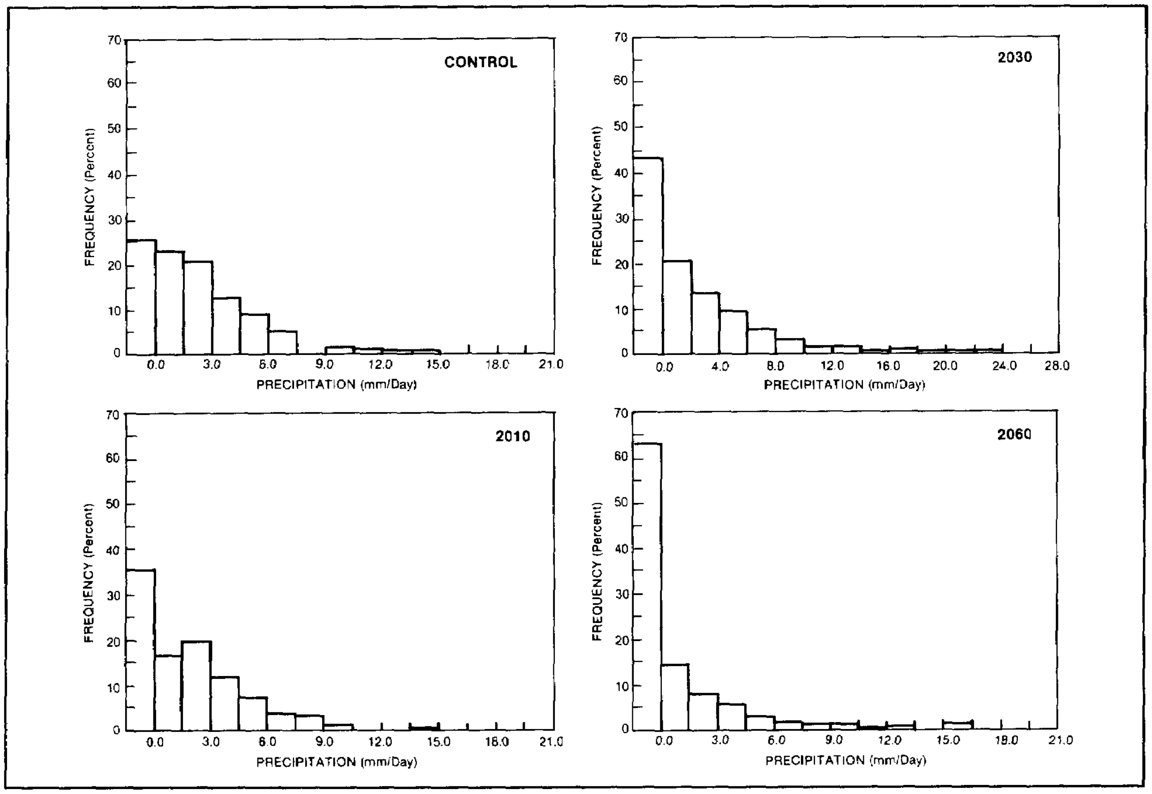

Figure 3-3. Sample of set precipitation distributions for the West Coast in April for specified years of the transient run (Rind et al., Volume I).

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.

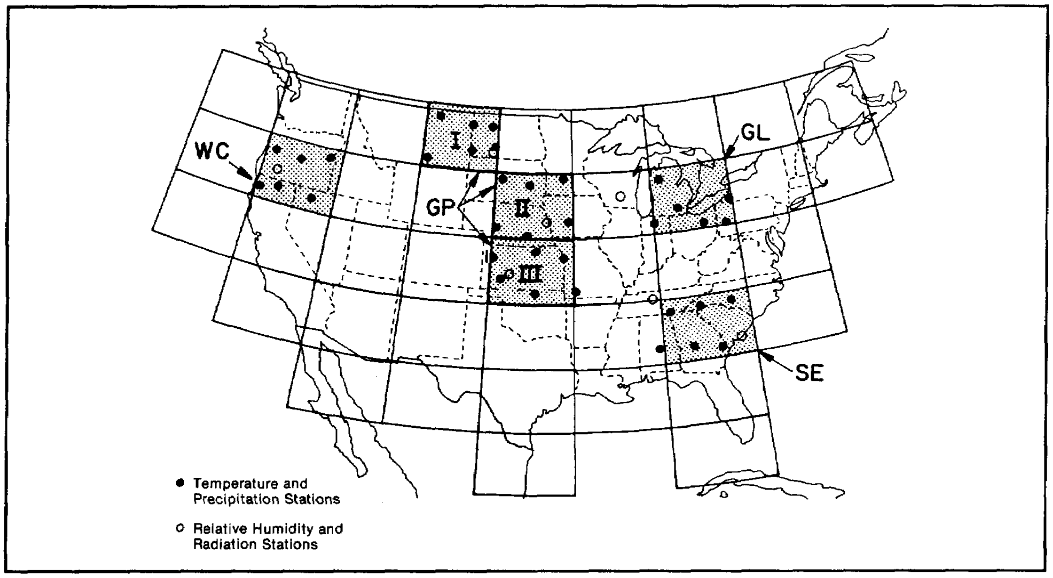

Figure 3-4. NCAR model grid cells and station locations.

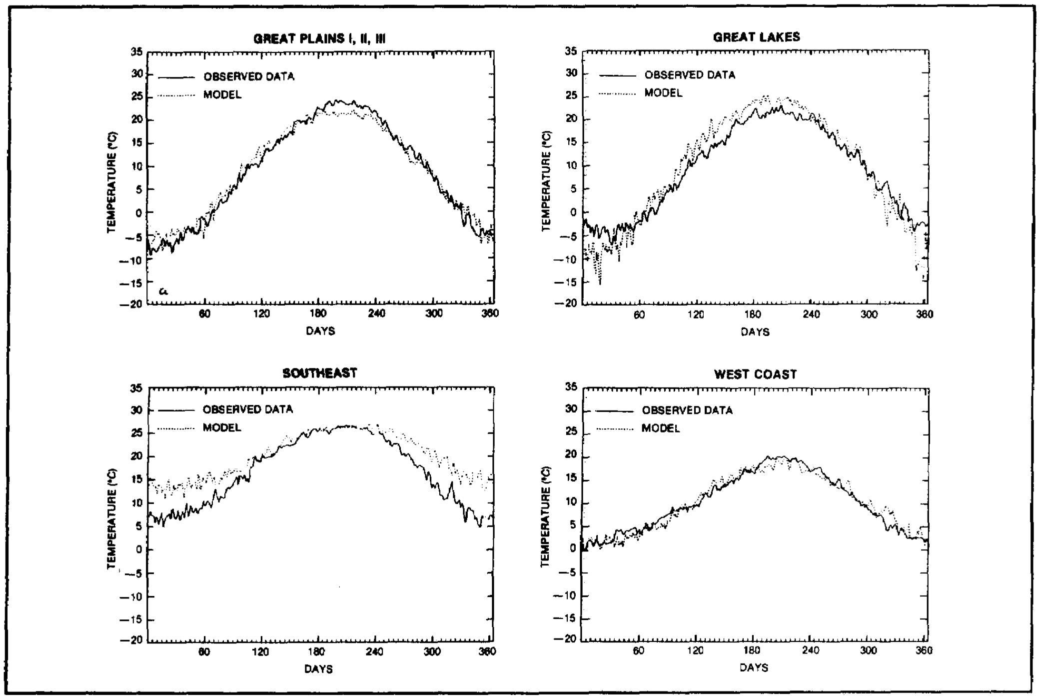

Figure 3-5. Average temperature for a 20-year average year (NCAR model and observations) (Mearns et al., Volume I).

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.

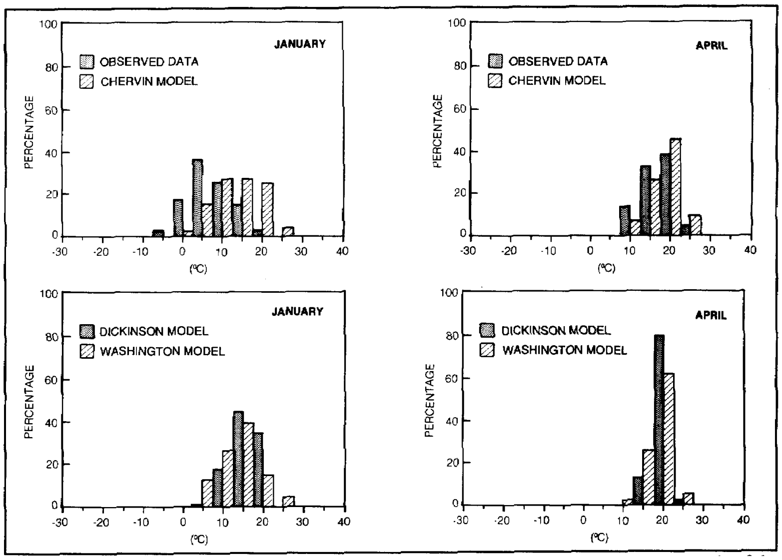

Figure 3-6. Histograms of daily temperature, observations and three model versions, for two key months of the Southeast grid (Mearns et al., Volume I).

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.

REFERENCES

American Meteorological Society. 1985. Flash floods: A statement of concern by the AMS. Bulletin of the American Meteorological Society 66(7):858-859.

Barbecel, O., and M. Eftimescu. 1973. Effects of Agrometeorological Conditions on Maize Growth and Development. Bucharest, Romania: Institute of Meteorology and Hydrology. pp. 10-31.

Bates, G.T., and G.A. Meehl. 1986. The Effect of C02 concentration on the frequency of blocking in a general circulation model coupled to a simple mixed layer ocean model. Monthly Weather Review 114:687-701.

Becker, RJ., and R.A. Wood. 1986. Heatwave. simulate subgrid-scale phenomena, must be Weatherwise 39(4):195-6.

Berger, A. 1980. Spectrum of climate variations and possible causes. In: Berger, A., ed. Climatic Variations and Variability: Facts and Theories. Dordrecht, Holland: D. Reidel. pp. 411-432.

Bourke, W. 1974. A multi-level spectral model. I. Formulation and hemispheric integrations. Monthly Weather Review 102:687-701.

Bourke, W., B. McAvaney, K. Puri, and R. Thurling. 1977. Global modeling of atmospheric flow by spectral methods. Methods in Computational Physics 17:267-324.

Bridger, C.A., F.P. Ellis, and H.L. Taylor. 1976. Mortality in St. Louis, Missouri, during heat waves in 1936, 1953, 1954, 1955, and 1966. Environmental Research 12:38-48.

Brinkmann, W.A.R. 1983. Variability of temperature in Wisconsin. Monthly Weather Review 111:172-180.

Chervin, R.M. 1986. Interannual variability and seasonal predictability. Journal of the Atmospheric Sciences 43:233-251.

Chervin, R.M. 1981. On the comparison of observed GCM simulated climate ensembles. Journal of the Atmospheric Sciences 38:885-901.

Clark, RA. 1987. Hydrological design criteria and climate variability. In: Soloman, S.I., M. Beran, and W. Hogg, eds. The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources. International Association of Hydrological Sciences Publ. No. 168. Oxfordshire: 1AHS Press.

Coleman, J.E. 1988. Climatic warming and increased summer aridity in Florida, U.S .A. Climatic Change 12:164-178.

Dare, P.M. 1981. A study of the severity of the midwestern winters of 1977 and 1978 using heating degree days determined from measured and wind chill temperatures. Bulletin of the American Meteorological Society 62(7):674-682.

Diaz, H.F. and R.G. Quayle 1980. The climate of the United States since 1895: Spatial and temporal changes. Monthly Weather Review 108:249-266.

Dickinson, R.E., A. Henderson-Sellers, P.J. Kennedy, and M.F. Wilson. 1986. Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model. NCAR Technical Note 275. Boulder, CO_2: National Center for Atmospheric Research.

Ellis, F.P. 1972. Mortality from heat illness and heat-aggravated illness in the U.S. Environmental Research 5(1):1-58.

Emmanuel, K.A. 1987. The dependence of hurricane intensity on climate. Nature 326:483-485.

Emmanuel, K.A. 1988. Toward a general theory of hurricanes. American Scientist 76(4):370-379.

Gibbs, WJ. 1984. The great Australian drought: 1982-1983. Disasters 8/2/84:89-104.

Gibbs, WJ., J.V. Maher, and M.J. Coughlan. 1975. Climatic variability and extremes. In: Pittock, A.B. LA. Frakes, D. Jenssen, JA. Peterson, and J.W. Zillman, eds. Climatic Change and Variability. Cambridge, United Kingdom: Cambridge University Press. pp. 135-150.

Hansen, J., I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, G. Russell, P. Stone. 1988. Global climate changes as forecast by the Goddard Institute for Space Studies three-dimensional model. Journal of Geophysical Research 93(D8):9341-9364.

Heathcote, R.L. 1985. Extreme event analysis. In: Kates, R.W., J.H. Ausubel, and M. Berberian, eds. Climate Impact Assessment, SCOPE 27. Chichester, United Kingdom: John Wiley and Sons.

Henz, J.F., and V.R. Scheetz. 1976. The big Thompson flood of 1976 in Colorado. Weatherwise 29(5):278-285.

Herbert, P.J., and G. Taylor. 1979. Everything you always wanted to know about hurricanes. Weatherwise 32(2):61-67.

Jones, T.S., et al. 1982. Morbidity and mortality associated with the July 1980 heat wave in St. Louis and Kansas City, MO. Journal of the American Medical Association 247:3327-3331.

Kalkstein, L.S., R.E. Davis, JA. Skindlov, and K.M. Valimont. 1987. The impact of human-induced climate warming upon human mortality: A New York case study. Washington, DC: U.S. Environmental Protection Agency.

Katz, R.W. 1984. Procedures for Determining the Statistical Significance of Changes in Variability Simulated by an Atmospheric General Circulation Model. Climate Research Institute Report No. 48. Corvallis, OR: Oregon State University.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. 1987. Potential Impacts of Climate Change on Electric Utilities. Albany, NY: New York State Energy Research and Development Authority. Report 88.2.

Lough, J.M., T.M.L. Wigley, and J.P. Palutikof. 1983. Climate and climate impact scenarios for Europe in a warmer world. Journal of Climate and Applied Meteorology 22:1673-1684.

Ludlum, D.M. 1988. Weatherwatch (for September). Weatherwise 41(6):354-355.

Manabe, S., and D.G. Hahn. 1981. Simulation of atmospheric variability. Monthly Weather Review 109:2260-2286.

McQuigg, J.D. 1981. Climate variability and crop yield in high and low temperature regions. In: Back W., J. Pankrath, and S.H. Schneider, eds. Food-Climate Interactions. Dordrecht, Holland: D. Reidel Publishing Company. pp. 121-138.

Mearns, L.O., S.H. Schneider, S.L. Thompson, and L.R. McDaniel. 1989. Analysis of climate variability in general circulation models: comparison with observations and changes in variability in 2xC02 experiments. Journal of Geophysical Research (accepted).

Mearns, L.O., R.W. Katz, and S.H. Schneider. 1984. Extreme high-temperature events: Changes in their probabilities with changes in mean temperature. Journal of Climate and Applied Meteorology 23:1601-1613.

Mederski, H.J. 1983. Effects of water and temperature stress on soybean plant growth and yield in humid temperature climates. In: Raper, C.D., and P.J. Kramer, eds. Crop Reactions to Water and Temperature Stresses in Humid, Temperate Climates. Boulder, CO: Westview Press. pp.35-48.

Meehl, G. 1989. Seasonal cycle forcing of El Nino phenomena in a coupled ocean-atmosphere model. Submitted to Science.

Mitchell, J.M. 1976. An overview of climatic variability and its causal mechanisms. Quaternary Research 6:481-493.

Mogil, H.M., A. Stern, and R. Hagen. 1984. The great freeze of '83: Analyzing the causes and the effects. Weatherwise 37(6):304-308.

Neild, R.E. 1982. Temperature and rainfall influences on the phenology and yield of grain soybean and maize. Agricultural Meteorology 27:79-88.

Newman, J.E. 1978. Drought impacts on American agricultural productivity. In: Rosenberg, N.J., ed. North American Droughts. Boulder, CO: Westview Press. pp. 43-63.

Oeschsli, F.W., and R.W. Buechley. 1970. Excess mortality associated with three Los Angeles September hot spells. Environmental Research 3:277-284.

Oliver, J. 1981. The nature and impact of Hurricane

Allen - August 1980. Journal of Climatology 1:221-235.

Parry, M.L. 1978. Climatic Change, Agriculture and Settlement. Folkstone, United Kingdom: Dawson.

Pittock, A.B. 1975. Patterns of variability in relation to the general circulation. In: Pittock, A.B., LA. Frakes, D. Jenssen, JA. Peterson, J.W. Zillman, eds. Climatic Change and Variability. Cambridge, United Kingdom: Cambridge University Press. pp. 167-178.

Policansky, D. 1977. The winter of 1976-77 and the prediction of unlikely weather. Bulletin of the American Meteorological Society 58(10):1073-1074.

Quirk, W.J. 1981. Climate and energy emergencies. Bulletin of the American Meteorological Society 62(5):623-631.

Reed, D.N. 1986. Simulation of time series of temperature and precipitation over eastern England by an atmospheric general circulation model. Journal of Climatology 6:233-257.

Reibsame, W.E. 1988. Adjusting water resources management to climate change. Climatic Change 13:69-97.

Rind, D., R. Goldberg, and R. Ruedy. 1989. Change in climate variability in the 21st century. Climatic Change 14:5-37.

Rosenberg, N.J., ed. 1979. Drought in the Great Plains: Research on Impacts and Strategies. Littleton, CO: Water Resources Publications.

Rosenberg, N.J., ed. 1978. North American Droughts. Boulder, CO: Westview Press.

Sanders, J.F. 1982. The hurricane dilemma. Weatherwise 35(4):174-178.

Shugart, H.H., M.Y. Antonovsky, P.G. Jarvis, and A.P. Sandford. 1986. C02,. climatic change, and forest ecosystems. In: Bolin, B., B.R. Doos, J. Jager, and R.A. Warrick, eds. The Greenhouse Effect, Climatic Change, and Ecosystems. SCOPE 29. Chichester, United Kingdom: John Wiley and Sons. pp.475-521.

Schwarz, H.E. 1977. Climatic change and water supply: how sensitive is the Northeast? In: Climate, Climate Change and Water Supply. Washington, DC: National Academy of Sciences. pp. 111-120.

Shaw, R.H. 1983. Estimates of yield reductions in corn caused by water and temperature stress. In: Raper, C.D., and PJ. Kramer, eds. Crop Reactions to Water and Temperature Stresses in Humid, Temperate Climates. Boulder, CO: Westview Press. pp.49-66.

Soloman, A.M., and D.C. West. 1985. Potential responses of forests to C02-induced climate change. In: White, M.R., ed. Characterization of Information Requirements for Studies of C02 Effects: Water Resources, Agriculture, Fisheries, Forests, and Human Health. U.S. Department of Energy. DOE/ER-0236. pp. 145-170.

Thompson, L.M. 1968. Weather and technology in the production of corn. In: Purdue Top Farmer Workshop, Corn Production Proceedings. West Lafayette, IN: Purdue University. pp. 3-19.

Trenberth, K.E., G.W. Branstator, and P.A. Arkin. 1988. Origins of the 1988 North American drought. Science 242:1640-1645.

Van Loon, H. and J. Williams. 1978. The association between mean temperature and interannual variability. Monthly Weather Review 106:1012-1017.

Warrick, RA. et al. 1975. Drought Hazard in the United States: A Research Assessment. Boulder, CO: University of Colorado. IBS Monograph No. NSF-RA-E-75-004.

Washington, W.M., and GA. Meehl. 1984. Seasonal cycle experiment on the climate sensitivity due to a doubling of C02 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model. Journal of Geophysical Research 89(D6):9475-9503.

White, G.F. et al. 1975. Flood Hazard in the U.S.A. Research Assessment. Boulder, CO: University of Colorado. IBS Monograph No. NSF-RA-E-75-006.

Wilford, J.N. 1988. Vast Persistent Pattern Spreading Heat Wave. The New York Times, p. 1; July 19.

Wilhite, D.A., and M.H. Glantz. 1987. Understanding the drought phenomenon: The role of definitions. In: Wilhite, D.A., and W. Easterling, eds. Planning for

Drought. Boulder, CO: Westview Press. pp. 11-27.

Wilson, C.A., and J.F.B. Mitchell. 1987. Simulated climate and C02 induced climate change over Western Europe. Climatic Change 10:11-42.

CHAPTER 4
METHODOLOGY

NEED FOR CLIMATE CHANGE SCENARIOS

As discussed in Chapter 2: Climate Change, there is a scientific consensus that increased atmospheric concentrations of greenhouse gases will likely increase global temperatures, and that such a global temperature increase will likely increase global precipitation and sea levels. There is no consensus on how regional climates may change. We do not know whether temperatures will rise in all regions; we do not know whether precipitation in any particular region will rise or fall or whether we will have seasonal changes, and we are uncertain about the rate and magnitude of change. As discussed in Chapter 3: Climate Variability, scientists do not know how variability -- that is, the frequency of droughts, storms, heat waves, and similar phenomena -- may change. Without knowing how regional climate may change, we cannot predict impacts.

Despite these uncertainties, we can get a sense of what the future may look like through the use of scenarios. Scenarios are plausible combinations of conditions that may be used to illustrate future events. They may be used to identify possible effects of climate change and to evaluate responses to those effects. To incorporate uncertainties surrounding regional climate change, regional scenarios should include a variety of potential climate changes consistent with the state of knowledge regarding global warming. By analyzing many scenarios, we may be able to identify the direction and relative magnitude of impacts. Yet, unless scenarios have probabilities assigned to them, predictions of future impacts cannot be made. In this report, probabilities are not assigned and results do not represent predictions. Only the direction of change and relative magnitude are identified. The scenarios used in this report do not represent the entire range of possible climate change. Thus, the range of effects identified does not represent the entire range of potential effects.

SCENARIO COMPONENTS

To assess the potential effects of global climate change, regional scenarios of such change should have the following characteristics:

1. The scenarios should be internally consistent with global warming caused by increases in greenhouse gas emissions. A doubling of the CO_2 concentration in the atmosphere is thought to increase global temperatures by approximately 1.5 to 4.5°C (3 to 8°F). The regional temperature changes and seasonal distributions may be higher or lower, as long as they are internally consistent with the global range.

2. The scenarios must include a sufficient number of meteorological variables to meet the requirements for using effects models. These effect models include models of crop growth, forest succession, runoff, and other systems. Some models of the relationship between climate and a system use only temperature and precipitation as climate variables, while others also need solar radiation, humidity, winds, and other variables.

3. The meteorological variables should be internally consistent. While a scenario is not a prediction, it should at least be plausible. The laws of physics limit how meteorological variables may change in relationship to each other. For example, if global temperatures increase, global precipitation must also rise. Regional changes should be internally consistent with these large-scale changes.

4. The scenarios should provide meteorological variables on a daily basis. Many of the effects models used in this study, such as crop yield and hydrology models, need daily meteorological inputs.

5. Finally, the scenarios should illustrate what climate would look like on a spatial scale fine enough for effects analysis. Many effects models consider changes in individual stands of trees or farm fields. To run them, scenarios must illustrate how climate may change locally.

TYPES OF SCENARIOS

Two questions should be answered in analyzing the potential impacts of the greenhouse effect: What would be the effects of a large climate change in the future? How quickly will the effects become apparent over time? The first question asks what the world will be like in the future; the second is about the speed of change and the sensitivity of the system.

One way of examining the first question is to use scenarios of an equilibrium future climate. Climate equilibrium is defined as climate in which average conditions are not changing (although year-to-year variations could still occur).

A drawback of an equilibrium scenario is that it occurs at an arbitrary point in the future and assumes that the climate has reached a stable level corresponding with the higher concentrations of greenhouse gases. It does not indicate how climate may change between now and the equilibrium condition or how soon effects may be seen. Furthermore, a "stable" climate has never happened, nor is it likely to occur.

To help identify sensitivities and give a sense of when effects may occur, this study uses transient scenarios of climate change. A transient scenario is a scenario of how climate may change over time.

The options for creating regional scenarios of global warming include the following:

1. arbitrary changes in climate;
2. analog warming; and
3. use of general circulation models.

Arbitrary Changes

A simple way of constructing a scenario is to assume that climate variables change by some arbitrary amount. For example, one could assume that temperatures increase by 2 or 4°C, or that rainfall rises or falls by 10% and all other variables are held constant. Such scenarios are relatively easy to use and can help to identify the sensitivities of systems to changes in different variables. To determine how sensitive a system is to temperature alone, one could hold other variables at current climate levels and change temperature by arbitrary amounts.

A major drawback to using scenarios with arbitrary changes is that they may not be realistic, since evaporation, precipitation, wind, and other variables will most likely change if global temperatures change. A combination of unrealistic meteorological changes may yield an unrealistic effect. We are not sure how other meteorological variables would change on a regional scale if temperature rose a certain amount. Thus, scenarios with arbitrary changes may be useful for determining sensitivities to particular variables but not for determining the possible magnitudes of effects.

Analog Warming

Many climatologists have advocated the use of historic warming periods as an analog of how a future warming may affect regional climates (Vinnikov and Lemeshko, 1987). The instrumental weather record can be used by comparing a cool decade on record, such as the 1880s, with a warm decade, such as the 1930s (Wigley, 1987), or by comparing a decade such as the 1930s with the present.

Paleoclimatic data may also be incorporated into an analog warming scenario. For example, 6,000 years ago the temperatures were about 1°C warmer. Paleoclimatologists have determined how rainfall and temperature patterns on a broad regional scale differed in the past. The changes associated with past climates that were warmer than now may be used as an analog warming scenario.

The advantage of using an analog is that it gives a realistic sense of how regional and local weather patterns change as global climate warms. For example, climate data from 1880 to 1930 show how daily and local weather changed during a warming period.

However, analogs have several drawbacks. First, they are not consistent with the range of global warming now thought likely under the greenhouse effect: 1.5 to 4.5°C. The warmest period of the last 125,000 years was 1°C warmer than the present temperature. (Although the Pliocene Epoch (2 to 5 million years ago) had global temperatures several degrees higher than now, there is virtually no information on the regional distribution of temperature and rainfall during that period.) In addition, the past warmings were not necessarily caused by changes in the concentration of greenhouse gases, but may have been due to such factors as shifts in the inclination of the Earth's axis. These factors caused different regional climate changes than would be associated with increases in radiative forcing. Second, paleoclimatic and historic records do not provide enough detail to conduct comprehensive analysis of the 1°C warming. Paleoclimatic records only indicate broad regional patterns of change for a few variables, such as temperature, rainfall, and solar radiation. We cannot discern local, daily, or interannual climate from these records. Even using the 1930s data presents some problems. Daily records are available only for temperature and rainfall. Some effects models need more variables, such as wind or radiation. Furthermore, the number of weather stations with 1930s data is limited, which could present problems for creating comprehensive regional scenarios.

General Circulation Models (GCMs)

GCMs are dynamic models that simulate the physical process of the atmosphere and oceans to estimate global climate. These models have been developed over two decades and require extensive computations to run. They can be run to estimate current climates and the sensitivity of climate to different conditions such as different compositions of greenhouse gases. The GCMs are often used to simulate climate caused by a doubling of carbon dioxide levels, also referred to as doubled CO_2. Estimates of climate change caused by this effective doubling of CO_2[1] are referred to as "doubled CO_2 scenarios." Output is given in regional grid boxes.

CCMs have several advantages over the other approaches for creating scenarios. First, the models are used to estimate how global climate may change in response to increased concentrations of greenhouse gases. Thus, regional outputs are internally consistent with a global warming associated with doubled CO_2. Second, the estimates of climate variables (for example, rainfall, temperature, and humidity levels) are physically consistent within the bounds of the model physics. Third, GCMs estimate outputs for many meteorological variables (including wind, radiation, cloud cover, and soil moisture) providing enough input for effects models. Fourth, GCMs simulate climate variability on at least a daily basis.

Among the most important limitations are the GCMs' simulations of the oceans. The oceans play a critical role in determining the rate of climate change, regional climate differences, and climate variability. The GCMs, however, are coupled to relatively simple models of ocean circulation, which either treat the oceans as a "swamp" or only model the upper layers of oceans. The models' assumptions oversimplify the transfer of heat to and from the oceans. In addition, the GCMs simplify other important factors that affect climate, including cloud cover and convection, sea ice, surface albedo (the amount of light reflected, rather than absorbed, from the surface) and land surface hydrology (i.e., soil moisture), which may also contribute to uncertainty about the estimates of climate change (Dickinson, 1986; Schlesinger and Mitchell, 1985; Gates, 1985). For example, some of the GCMs model soil moisture storage in a simple manner, assuming the soils act like a "bucket." (There have been recent improvements on this method.) This method of modeling raises uncertainties concerning estimates of runoff from the models. The way GCMs simulate such important climate factors as oceans, clouds, and other features casts some doubt on the validity of the magnitude of global warming estimated by the models. (For a further discussion of the role of oceans in climate change, see Chapter 2: Climate Change. For a discussion of the GCMs' ability to estimate climate variability, see Chapter 3: Climate Variability.)

One of the major disadvantages of using GCMs for effects analysis is their low spatial resolution. GCMs give outputs in grid boxes that vary in size from 4 by 5 degrees latitude to as much as 8 by 10 degrees longitude. Figure 4-1 shows the grid boxes from the Goddard Institute for Space Studies (GISS)

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[1] The "effective doubling of CO_2" means that the total radiative forcing of all greenhouse gases (CO_2, CH_4 N_20, CFCs, etc.) is the same as the radiative forcing caused by doubling carbon dioxide concentrations, over midcentury levels, alone. In other words, the combination of all greenhouse gases has the same radiative forcing as simply doubling CO_2.

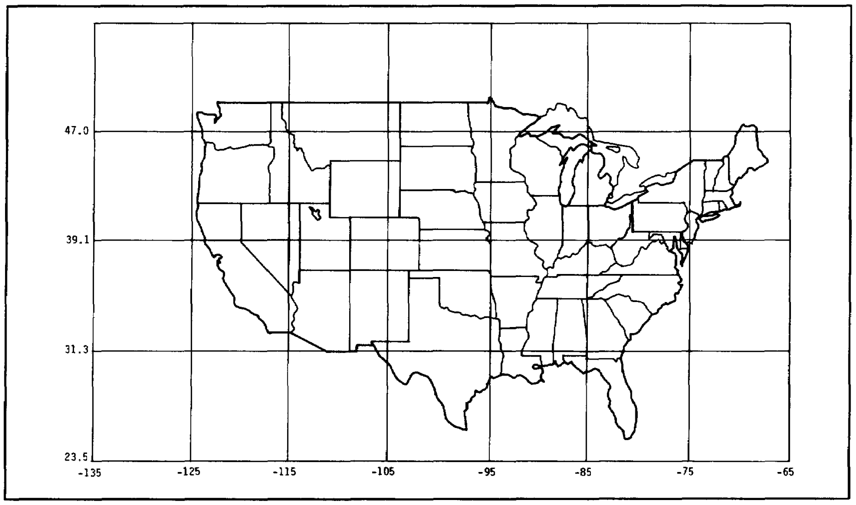


Figure 4-1. GISS model of the United States.

model overlaid on a map of the United States. Each grid box is 8 by 10 degrees and is an area larger than France (Mitchell, 1988). Within each grid box, the actual climate may be quite variable. For example, although both are in the same grid box, the weather in southern Washington State may be quite different from the weather in northern California. The models, however, do not account for variations within each grid box. For any simulated time, they provide a single value for temperature, for rainfall, and for other variables for the entire area of the box.

A second disadvantage for effects analysis, which may be more critical than the first, is that GCMs generally do not accurately simulate current regional climate conditions. In general, the accuracy of GCM climate estimates decreases with increasing resolution. The GCMs do a reasonable job of estimating observed global and zonal climates, but the estimates of regional climate are, in many cases, far from observed conditions. This is shown in Table 2-2 (see Chapter 2: Climate Change), adapted from Grotch (1988), which displays GCM temperature estimates and actual observations on different scales. GCM estimates of rainfall are less reliable on a regional scale. As Grotch points out, the disparities between GCM estimates of current regional climate and actual conditions calls into question the ability of GCMs to predict climate change on a regional scale.

The disparities among GCM estimates on a regional scale are due to a number of factors. One of the most important is the simplified assumptions concerning the oceans. The assumptions on other factors such as cloud cover, albedo, and land surface hydrology also affect regional estimates. The GCMs also simplify topographic features within grid boxes, such as the distribution of mountains or lakes. The large size of the grid boxes means that these features are oversimplified on a geographic scale. This contributes to uncertainty regarding estimates of regional climate change. In sum, as Grotch concluded, GCM estimates of regional climate change should not be taken as predictions of regional climate change. They should be interpreted as no more than illustrations of possible future regional climate conditions.

CHOICE OF DOUBLED CO_2 SCENARIO

GCM outputs were employed as a basis for constructing the scenarios to be used in our report because they produce the best estimate of climate change due to increased greenhouse gas concentrations and they produce regional climate estimates internally consistent with doubled CO_2 concentrations. Yet, GCMs are relatively new tools that need a great degree of refinement. Their results must be applied with caution. The regional GCM estimates of climate change are considered to be scenarios, not predictions. Given the uncertainties about GCM estimates of daily and interannual variability (see Chapter 3: Variability), a conservative approach involves using average monthly changes for each grid box.

The scenarios described in this chapter are a hybrid between GCM outputs and historic weather data. The estimates of average monthly change in temperature, precipitation, and other weather variables are used from GCM grid boxes. Model simulations of monthly doubled CO_2 conditions are divided by model simulations of average monthly current conditions in each grid. The ratios of $(2xCO_2)$:$(1xCO_2)$ are multiplied by historic weather conditions at weather stations in the respective grid boxes. Parry et al. (1987) used this approach in an analysis of impacts of climate change on agriculture. Thus, if a grid box is estimated to be 2°C warmer under the GCM doubled CO_2 run, all stations in that grid are assumed to be 2°C warmer in the doubled CO_2 scenario. The effect of this is to keep geographic variation from station to station within a grid the same as in the historic base period. Furthermore, interannual (year to year) and daily variability remain the same. If rainfall occurs 10 days in a month, in the scenario it also occurs 10 days in the month, and the amount of rainfall is adjusted by the GCM output. Since these scenarios are hybrids between GCM average monthly estimates and daily historic weather records, these scenarios are not strictly GCM scenarios. Each scenario is referred to by the GCM, whose monthly output serves as its base (e.g., the "GISS scenario").

The years 1951-80 were chosen as the base period to which average doubled CO_2 changes were applied. Several decades of data give a wide range of warm, cold, wet, and dry years. Since the data are from the most recent decades, they are the most complete historic data available. A complete daily record for a number of weather variables only began in 1948.

GCMs Used

To obtain a range of scenarios, output from three GCMs was used:

- Goddard Institute for Space Studies (GISS) (Hansen et al., 1988);
- Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1987); and
- Oregon State University (OSU) (Schlesinger and Zhao, 1988).

The average seasonal temperature and precipitation for the U.S. gridpoints for each model are displayed in Figure 4-2. All three models estimate that average temperatures over the United States would rise, but they disagree on the magnitude. OSU gives 3°C, GISS 4.3°C, and GFDL 5.1°C. The seasonal patterns are different, with GISS having a larger warming in winter and fall, GFDL having the highest temperature change in the spring, and OSU having little seasonal variability. All three models estimate that annual precipitation over the United States would increase. GISS and OSU estimate that annual precipitation would rise, respectively, by 73 millimeters (2.92 inches) and 62 millimeters (2.48 inches), while GFDL estimates a rainfall increase of only 33 millimeters (1.31 inches). The first two models have precipitation increases in all four seasons, while GFDL has a decline in summer rainfall. As can be seen in the regional chapters, the models show greater disagreement on the direction and pattern of regional rainfall changes than on regional temperature. Overall, OSU appears to be the "mildest" scenario, with the lowest temperature rise and largest increase in precipitation. GFDL appears to be the most "extreme," with the highest temperature rise, the smallest increase in precipitation, and a decrease in summer rainfall. Some of the important parameters in the three GCMs are displayed in Table 4-1.

The "extreme" values in the GFDL doubled CO_2 scenario are due, in part, to assumptions made in t9e model run used in this report. That run did not constrain sea surface temperature and sea ice, which yielded seasonal extremes in the northern hemisphere. A later run, produced too late for use in this study, constrained sea surface temperature and sea ice to observed values. Both runs yield the same average global warming of 4.0°C, while the later run has greater seasonal extremes in the southern hemisphere. Both runs show a large decrease in summer soil moisture (Wetherald, personal communication, 1988).

Limitations

A major limitation of the doubled CO_2 scenarios used for this study is the lack of temporal and spatial variability. By applying average monthly changes to the historic data set, it is assumed that the

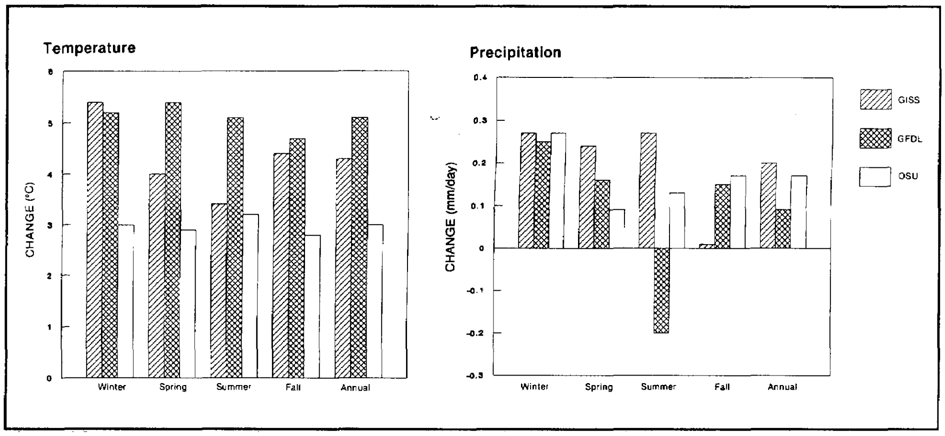


Figure 4-2. Average changes in temperature (° C) and precipitation (mm/day) over the grid boxes of the lower 48 states ($2xCO_2$ less $1xCO_2$).

daily and interannual patterns of climate remain the same. This assumption is probably unrealistic, since a change in average conditions will probably lead to a change in variability. Furthermore, holding variability constant can have an impact on effects analysis.

Most climate-sensitive systems are sensitive to climate variability. For example, riverflow is very sensitive to the amount and intensity of rainstorms. Certain crops are sensitive to consecutive days with temperatures above a certain level. The studies do not identify how these and other systems could be affected by changes in temporal climate variability. Holding spatial variability within a grid box constant also affects the results of the analyses performed for this report. Climate change may also lead to changes in wind patterns, which could change storm patterns, cloud distribution, deposition of air pollutants, and other systems. In addition, the years 1951 to 1980 were a period of relatively low weather variability in the United States. Only adjusting average conditions from the base period in the scenarios may underestimate potential increases invariability. (For further discussion, see Chapter 3: Variability.)

The choice of the three doubled CO_2 scenarios does not necessarily bracket the range of possible climate change in the latter half of the next century. Due to the uncertainties about the rate and magnitude of global warming, it is possible that average global temperatures could be lower or higher than indicated by the models. Other climate variables could be different too. Thus, these scenarios should be interpreted as illustrations of possible future conditions, not as predictions. Furthermore, we did not assign probability to these scenarios. Currently, there is not enough information or a methodology for making such a determination.

If current emission trends continue, the effective doubling of CO_2 concentrations will occur around the year 2030. However, that estimate does not account for some recent developments that may slow the increase in greenhouse gas concentrations. If implemented, the Montreal Protocol would cut emissions of chlorofluorocarbons (CFCs) by 50%. If an international agreement is reached on reduction of nitrogen oxides (NO_X), the concentration of nitrogen dioxide (N_2O) may be slightly reduced. Pollution control measures in countries such as the United States may also reduce concentrations of low-level ozone, another greenhouse gas. Thus, the effective doubling of CO_2 may happen after 2030.

As discussed in Chapter 2: Climate Change, the change in climate potentially caused by CO_2 doubling would not occur at the same time as the increase in greenhouse gas concentrations. The oceans absorb greenhouse gases and heat from the atmosphere and serve to delay the warming. The full extent of climate change associated with CO_2 doubling could take several decades or more and may not occur until the latter half of the next century.

Table 4.1 Major Features for the Three GCMs[a]

GCM	When calculated	Model resolution (lat. x long.)	Model levels[b]	Diurnal cycle	Base 1 x CO_2 (ppm)	Temp for doubled CO_2 (°C)	Increase in global precipitation (%)
GISSc	1982	7.83 x 10[d]	9	yes	315	4.2	11
GFDLd	1984-85	4.44 x 7.5[d]	9	no	300	4.0	8.7
OSU	1984-85	4.00 x 5.0[d]	2	no	326	2.8	7.8
GISS Transient	1984-85	7.83 x 10[d]	9	yes	315 (in 1958)	--	--

[a] All models are global in extent and have an annual cycle. All models have a smoothed topography that varies between models. The later GFDL has been added for information. All models (except the transient) give data for the present climate ($1xCO_2$) and double CO_2 climate ($2xCO_2$).

[b] All models make calculations for surface conditions as well as for the listed upper-air levels.

[c] A gridpoint model with stated resolution

[d] This is a spectral model that has 15 waves.

Note: Oceans in Models:

GISS: This model has a slab ocean not over 65 meters deep; it has some variation of mixed depth over the seasonal cycle (for example, the depth is shallower in summer than winter in mid-latitudes). It has a specified pseudo ocean heat transport designed to reproduce the present day sea surface temperature (SST) in the simulation of the present climate. Ice thickness is predicted. For the GISS transient runs, the ocean depth was not limited in this way. In it, the average annual maximum mixed-layer depth was 127 inches.

GFDL: The slab ocean is 68 meters deep. There is no horizontal heat transport that would make the present day SST come out exactly right. Ice thickness is predicted.

OSU: This model has a slab ocean that is 60 meters deep (only 5 meters deep during spin-up period). It does not have heat transport that would force the model to reproduce the model to reproduce the present dat SST (this is being added in 1989).

In this report, results from doubled CO_2 scenarios are generally not associated with a particular year. When analysis is necessary, we have generally assumed that the CO_2 warming will occur in 2060. In some cases, researchers assumed a different time period for CO_2 warming, and those exceptions are noted as appropriate in the text.

The doubled CO_2 scenarios are often interpreted as estimates of future static (equilibrium) conditions. The assumption that the concentration of greenhouse gases becomes constant at doubled CO_2 levels is an arbitrary one. In fact, if emissions are not limited, concentrations could become greater and the global climate would continue to change. In many places in this report, responses are presented as if the climate stabilizes at doubled CO_2 conditions. Natural systems and society, however, may be responding and adapting to continuing and perhaps, accelerating changes in climate.

OPTIONS FOR CREATING TRANSIENT SCENARIOS

The options for developing transient scenarios are similar to the options for the doubled CO_2 scenarios:

1. arbitrary changes;
2. analog warming; and
3. GCM transient runs.

Arbitrary Changes

One could examine the manner in which a system responds to an arbitrary 1 or 2°C temperature warming and to small arbitrary changes in other variables. The problems of physically inconsistent assumptions about changes among variables and regions pertain here also. In addition, the arbitrary warming scenario gives no indication of when the warming may occur.

Analog Warming

Wigley (1987) has suggested using analogs as scenarios for climates that may occur within the next several decades. He noted that the warming from the late 19th century to 1940 was about 0.4°C, which may approximate the transient warming over the next two decades. The problem is that climate may change faster in the future than in the early 20th century. (The average decadal warming may be as much as 0.5°C, rather than the 0.1°C identified for earlier years.) Furthermore, the analog takes one only as far as a 0.5°C warming or, in the case of paleoelimatic records, a 1°C warming. It does not indicate what happens in the decades after the 0.5 to 1.0°C level is reached. In addition, the analog may not represent the regional distribution of climate associated with greenhouse forcing.

GCM Transient Runs

The Goddard Institute for Space Studies has modeled how global climate may change as concentrations of greenhouse gases gradually rise over the next century. This is called the transient run. GISS has modeled climate change under several assumptions of trace gas growth. The transient runs start in 1958 with the atmospheric concentrations of greenhouse gases that existed then. The concentrations of the gases and equivalent radiative forcing were estimated to increase from 1958 until an arbitrary point in the. future according to several different assumptions regarding trace gas growth. The GISS transient run yields daily climate estimates from 1958 until that arbitrary point.

For example, one of the transient scenarios, which is known as GISS A, assumes that trace gas concentrations continue to increase at historic rates and net greenhouse forcing increases exponentially. The scenario is run from 1958 to 2062. The end of the transient corresponds with a global warming equivalent to that of the equilibrium climate from the doubled CO_2 run. This scenario does not account for the potential reduction in CFC emissions due to the Montreal Protocol or for other activities that may reduce the growth in emissions. GISS B assumes a decreasing trace gas concentration growth rate such that climate forcing increases linearly (Hansen et al., 1988). It stops in 2029. GISS B includes volcanoes, while GISS A does not.

Since the GCMs are used to produce this transient run, the advantages and disadvantages of using this approach are the same as those described in the discussion of doubled CO_2 scenarios. In addition, the timing of the changes estimated by the GCMs is complicated by the uncertainties regarding the growth of greenhouse gas emissions and the roles of the oceans and clouds in delaying climate changes (Dickinson, 1986).

CHOICE OF TRANSIENT SCENARIO

This study used transient scenarios based on the GISS transient run because, of all the different approaches, only this one provides internally consistent estimates of climate change and allows examination of the entire range of climate change between current conditions and doubled CO_2 climate.

In creating the transient scenario, an approach similar to that used for the doubled CO_2 scenario was employed. Since relatively little confidence exists in the GCM's estimates of changes in interannual and daily variability, the monthly means were calculated for each decade of the transient. This process gives average decadal temperature, precipitation, and other changes. The average decadal temperature changes in GISS A and B for the United States are shown in Figure 4-3.

As in the doubled CO_2 scenario, the average meteorological changes from the transient are combined with a historic time series. What is different from the doubled CO_2 scenario is that a gradual change in temperature and other variables is mixed with a historic time series with its own variability. This can produce a regular oscillation.

In this study, the historic time series 1951-80 is used, and the transient monthly statistics are applied to the time series. The procedure for creating the transient scenario was to first linearly interpolate between decadal means. This smooths out the sharp decadal changes from the actual transient GISS results and is shown in Figure 4-4(a). The baseline 1951-80 weather data were repeated for 80 years, with the last 20 years consisting of a repetition of the 1951-70 data. Figure 4-4(b) shows the average U.S. temperatures for 1951-80 repeated for 80 years. The data transformations displayed in Figures 4-4(a) and (b) were done for data for each month for each grid box, site, and climate variable. The smoothed month-by-month transient data were added to the repeated 1951-80 data for each site and variable. Figure 4-4(c) displays the addition of the smoothed average U.S. transient temperatures with actual U.S. 1951-80 temperatures, repeated. Although there is a cooling from the 19505 to the 1960s, followed by a warming in the 19705, the underlying warming of the transient, which is 3.7°C by the middle of the 20505 in GISS A, is much greater than the variability in the base period.

Limitations

Since the transient scenarios were also derived from GCMs, the same limitations concerning temporal and spatial variability pertain as in the doubled CO_2 scenario. An additional limitation in the transient scenario is the rate of change. The GISS transient runs assume a gradual rate of change in temperature. The simplistic treatment of ocean circulation in the GCM affects the rate of warming estimated by the model. Broecker (1987) has shown that past climate changes may have been abrupt. Broecker, however, analyzed a global cooling, and the changes occurred over a much longer period than greenhouse warming. A sudden warming could mean that significant effects happen sooner and more suddenly than the results of the transient analysis used in this study indicate. The inclusion of the 1951-80 base period in the scenario yields short-term oscillations.

OTHER SCENARIOS

In a few cases, researchers used meteorologic data from the 19303 as an analog scenario. This scenario was used to provide additional information on the sensitivity of systems to climate change. In a few other cases, researchers only examined paleoclimatic records. In these cases, the goal was to determine how a system responded to past climate change.

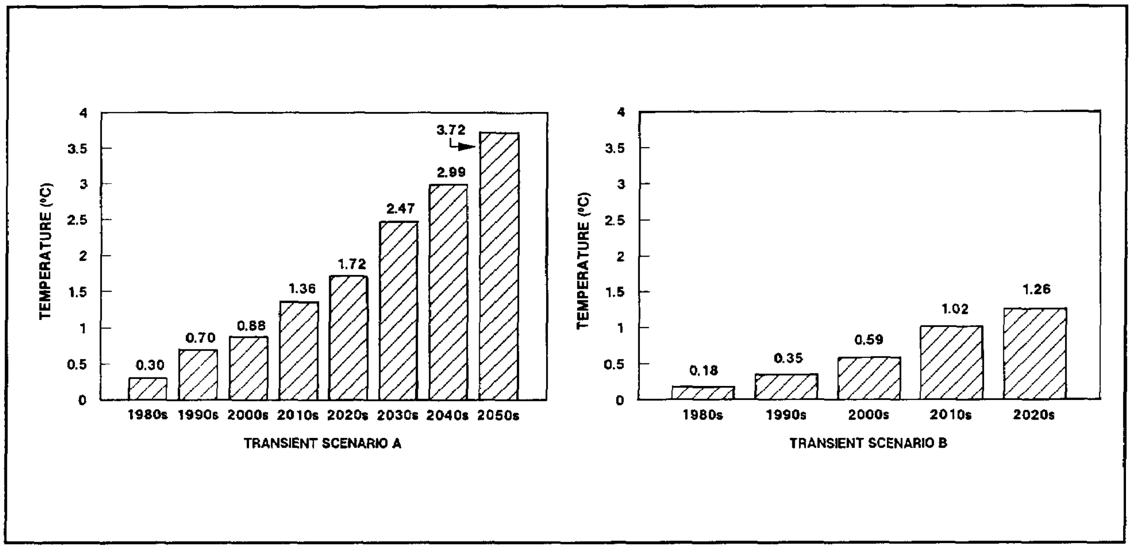


Figure 4-3. GISS transients "A" and "B" average decadal temperature change for lower 48 states gridpoints.

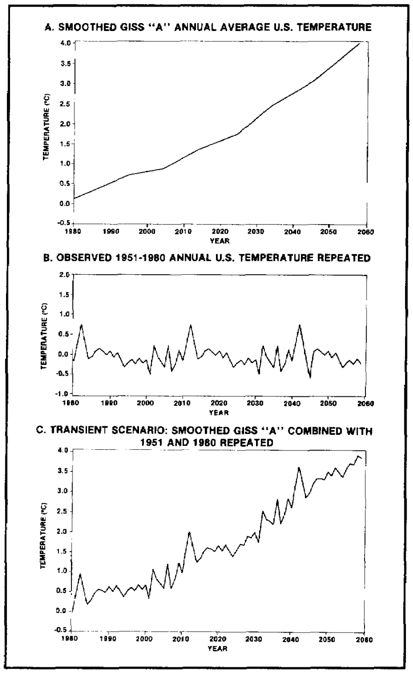


Figure 4-4. Transient scenarios (temperature change).

EPA specified that researchers were to use three doubled CO_2 scenarios, two transient scenarios, and an analog scenario in this study. Many researchers, however, did not have sufficient time or resources to allow for the use of all scenarios. EPA asked the researchers to run the scenarios in the following order, going as far through the list as time and resources allowed:

1. GISS doubled CO_2;

2. GFDL doubled CO_2;

3. GISS transient A;

4. OSU doubled CO_2;

5. Analog (1930 to 1939); and

6. GISS transient B;

Most researchers were able to use at least the GISS and GFDL doubled CO_2 scenarios. Comparison of results across studies may be limited because of inconsistent use of scenarios.

Sea Level Rise Scenarios

Unlike the climate scenarios, the alternative sea level rise scenarios were not based solely on the differences between various general circulation models. Instead, they were based on the range of estimates that previous studies have projected for the year 2100 (Hoffman et al., 1983, 1986; Meier et al., 1985; Revelle, 1983; Thomas, 1986), which have generally considered alternative rates of greenhouse gas emissions, climate sensitivity ranging from 1.5 to 4.5°C for a CO_2 doubling, and uncertainties regarding ocean expansion and glacial melting. Estimates for the year 2100 generally range from 50 to 200 centimeters.

This report uses three scenarios for the year 2100 -- 50, 100, and 200 centimeters -- and compares them to the current trend of 12 centimeters per century. Because most studies have not reported estimates for the intermediate years, we followed the convention of a 1987 National Research Council report (Dean et al., 1987) and interpolated sea level rise using a parabola. The rates of sea level rise assumed in this report are displayed in Figure 7-8 in Chapter 7: Sea Level Rise. Because various coastal areas are also sinking (and in a few cases rising), relative sea level rise at specific locations was estimated by adding current local subsidence trends. Note that sea level rise scenarios are presented for the year 2100, while doubled CO_2 scenarios are presented for the latter half of the It century.

EFFECTS ANALYSES

In this study, the preferred approach for analyzing potential impacts of climate change was to develop quantitative estimates. Most researchers estimated impacts by running models that simulate the relationship between weather and the relevant system. The climate scenarios were used as inputs into the models. Since the researchers had only several months to do the analysis, they used either "off-the-shelf" models or analytic techniques. In many cases, existing models were calibrated to new sites. This lack of time also limited the gathering of new data to a few studies.

A drawback of using empirical models of systems to estimate sensitivities is that the models are applied to climates for which they were not developed. The models estimate relationships with observed climate. This relationship is then extrapolated to an unprecedented climate. It is possible that in the new climate situation, the statistical relationship may be different owing to the crossing of a threshold or for some other reason. With the drawbacks of empirical models, the current statistical relationships are the best basis for quantitatively estimating sensitivities.

For the most part, researchers analyzed the potential effects of climate change on systems as they currently exist. Although these changes may be quite substantial, potential changes in populations, the economy, technology, and other factors were not considered. In some cases, researchers ran additional scenarios with assumptions about technological and other changes. In addition, potential responses to climate change were considered in some, but not all, cases. For these and many other reasons, the results should be interpreted only as an indication of the sensitivity of current systems to global warming, not as a prediction of what the effects will be.

In some situations, quantitative models of the relationship between climate and a particular system did not exist. In those cases, other approaches were used to try to identify sensitivities. Some researchers examined how systems responded to analog warmings. In other cases, expert judgment was used. This consisted of literature reviews to assemble information on sensitivities as they appear in the literature, and workshops and interviews to poll experts on how they thought systems would respond to global warming.

RESEARCH NEEDS

The scenarios used in this report help identify the sensitivities of systems to climate change. Because of the lack of confidence concerning regional estimates of climate change from GCMs, we cannot predict impacts. In order to predict the effects of climate change, major improvements need to be made in GCMs. These could take many years. In the meantime, we will continue to use scenarios to identify sensitivities. As with GCMs, scenarios can also be improved.

GCMs

To produce better estimates of regional climate change, both the resolution of GCMs and the modeling of physical processes need to be improved. The GCMs used for this report had large grid boxes, in which major geographic features, such as the Great Lakes or the Sierra Nevada Mountains, which have large impacts on local climate, were not well represented. Ideally, the higher the resolution, the better the representation of geographic features. But each increase in resolution means a large increase in computations and computing power needed to run the model. Furthermore, at high resolutions, the GCMs may require new parameterizations. The resolution should be increased at least to the point at which major geographic features are well represented in the models.

It is also important that the estimates of physical processes in the models be improved to increase the confidence about estimates of the magnitude and timing of changes. Three areas need the most attention: oceans, clouds, and hydrology. The oceans play an important role in delaying climate change and have a large influence on regional climates. However, the ocean models currently used in GCMs are relatively simple. Ocean models that better simulate the absorption and transport of heat and gases would give improved estimates of transient and regional climate change. Clouds are a major feedback to global warming and influence regional climate. More realistic modeling of clouds by GCMs would improve the estimates of the magnitude of global warming and regional change. Finally, more sophisticated hydrology in GCMs will yield better estimates of soil moisture and runoff, which will also improve estimates of regional climate changes.

Scenarios

The scenarios in this report were based on changes in average conditions, either at equilibrium (doubled CO_2) or due to a gradual change in average underlying conditions (transient). As pointed out in Chapter 3: Variability, many systems are quite sensitive to changes in the frequency and intensity of extreme events. In the future, scenarios should incorporate change in variability to help identify sensitivities to variability. Transient scenarios can also be improved. Such scenarios should be useful for testing sensitivities to changes in long-term climate trends as well as year-to-year variations. At the same time, it is important to keep scenarios simple. More detailed scenarios, involving a lot of data (such as daily data from GCMs) may be difficult to use. The more detailed the scenario, the more likely it will be applied incorrectly, which limits the ability to compare results by different researchers. In addition, scenarios should be simple, so the assumptions used in creating them can be easily understood. Designers of scenarios will have to wrestle with the competing desires of being more detailed and maintaining simplicity.

REFERENCES

Broecker, W.S. 1987. Unpleasant surprises in the greenhouse? Nature 328:123-126.

Dean, R.G., R.A. Darylrumple, R.W. Fairbridge, S.P. Leatherman, D. Nummendal, M.P. O'Brien, O.H. Pilkey, W. Sturges, R.L. Wiegel. 1987. Responding to Changes in Sea Level: Engineering Implications. National Research Council. Washington, DC: National Academy Press.

Dickinson, R.E. 1986. How will climate change: The climate system and modelling of future climate. In: Bolin, B., B.R. Doos, J. Jager, and R.A. Warrick, eds. Scope 29: The Greenhouse Effect, Climatic Change and Ecosystems. New York: John Wiley and Sons. pp. 221-231.

Gates, W.L. 1985. Modeling as a means of studying the climate system. In: MacCracken, M.C., and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy. DOE/ER-0237.

Grotch, S.L. 1988. Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data. Prepared for U.S. Department of Energy. TR041.

Hansen, J., I. Fung, A. Lacis, D. Rind, G. Russell, S. Lebedeff, R. Ruedy, and P. Stone. 1988. Global climate changes as forecast by the GISS 3-D model. Journal of Geophysical Research 93:9341-9364.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis. 1983. Efficient three-dimensional global models for climate studies: Models I and II. Monthly Weather Review 3(4):609-622.

Hoffman, J.S., D. Keyes, and J.G. Titus. 1983. Projecting future sea level rise. Washington, DC: U.S. Government Printing Office.

Hoffman, J.S., J. Wells, and J.G. Titus. 1986. Future global warming and sea level rise. In: Sigbjarnarson G., ed. Iceland Coastal and River Symposium. Reykjavik, Iceland: National Energy Authority.

Manabe, S., and R.T. Wetherald. 1987. Large scale changes in soil wetness induced by an increase in carbon dioxide. Journal of Atmospheric Sciences 44:1211-1235.

Meier, M.F. et al. 1985. Glaciers, ice sheets, and sea level. Washington, DC: National Academy Press.

Mitchell, J.F.B. 1988. Local effects of greenhouse gases. Nature 332:399-400.

Parry, M., T. Carter, N. Konijin, and J. Lockwood. 1987. The Impact of Climatic Variations on Agriculture: Introduction to the IIASA/UNEP Case Studies in Semi-Arid Regions. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Revelle, R. 1983. Probable future changes in sea level resulting from increased atmospheric carbon dioxide. In: Changing Climate. Washington, DC: National Academy Press.

Schlesinger, M.E., and J.F.B. Mitchell. 1985. Model projections of the equilibrium climatic response to increased carbon dioxide. In: MacCracken, M.D., and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. Washington, DC: U.S. Department of Energy. DOE/ER-0237.

Schlesinger, M., and Z. Zhao. 1988. Seasonal Climate Changes Induced by Doubled CO_2 or Simulated by the OSU Atmospheric GCM/Mixed Layer Ocean Model. Corvallis, OR: Oregon State University, Climate Research Institute.

Thomas, R.H. 1986. In: Titus, J.G., ed. Effects of Changes in Stratospheric Ozone and Global Climate. Washington, DC: U.S. Environmental Protection Agency and UNEP.

Vinnikov, K.Y., and NA. Lemeshko. 1987. Soil moisture content and runoff in the USSR territory with global warming. Journal of Meteorology and Hydrology No. 12.

Wigley, T.M.L. 1987. Climate Scenarios. Prepared for the European Workshop in Interrelated Bioclimate and Land-Use Changes. Boulder, CO_2: National Center for Atmospheric Research. NCAR 3142-86/3.

CHAPTER 5
FORESTS

FINDINGS

Global warming could significantly affect the forests of the United States. Changes could be apparent in 30 to 80 years, depending upon the region, the quality of a site, and the rate of climate change. There may be northward shifts in species ranges, dieback along the southern reaches of species ranges, and changes in forest productivity. Other stresses in combination with climate change may exacerbate these impacts. Different migration rates and climate sensitivities may result in changes in forest composition. Without large-scale reforestation, large reductions in the land area of healthy forests are possible during this century of adjustment to climate changes. Although climate fluctuations, timber harvests, disease outbreaks, wildfires, and other factors have affected forests during the last century, the magnitude of these changes is substantially less than those projected in response to climate changes considered in this report.

Range Shifts

- The southern ranges of many forest species in the eastern United States could die back as a result of higher temperatures and drier soils. The southern boundary could move several hundred to 1,000 kilometers (up to 600 miles) in a generally northward direction for the scenarios studied.

- The potential northern range of forest species in the eastern United States could shift northward as much as 600 to 700 kilometers (370 to 430 miles) over the next century. Actual northward migration could be limited to as little as 100 kilometers (60 miles) owing to the slow rates of migration of forest species. Without reforestation, full migration of eastern forests to potential northern distributions could take centuries. If climate change occurs too rapidly, some tree species may not be able to form healthy seeds, thus halting migration. Reforestation along northern portions of potential forest ranges could mitigate some of these impacts.

- If elevated CO_2 concentrations substantially increase the water-use efficiency of tree species, the southern declines would be alleviated.

- If climate stabilizes, forests might eventually regain a generally healthy status (over a period of several centuries). In the meantime, declining forests could be subject to increased fires, pest attacks, and replacement with low-value trees, grasslands, and shrubs. A continually changing climate could result in even greater dislocations among forests.

Productivity Changes

- Dieback along the southern limits of distribution of many species could result in productivity declines of 40 to 100%, depending on how dry soils become.

- Productivity could increase along the northern limits of some eastern tree species, particularly as slow-growing conifers are replaced by more rapidly growing hardwoods.

Combined Impacts With Other Stresses

- Large regions of severely stressed forests, combined with possible increases in fires, pests, disease outbreaks, wind damage, and air pollution, could produce major regional disturbances. These factors were not considered for this report.

- Additional impacts of changes in forests include reductions in biotic diversity, increased soil runoff and soil erosion, reduced aquifer recharge, changes in recreation, and changes in wildlife habitat.

Policy Implications

- Institutions such as the U.S. Forest Service, state forest agencies, and private companies should begin to consider how to factor climate change in their long-term planning. Global climate change may need to be a factor in the Forest Service's 50-year planning horizon.

- Where U.S. forests are clearly reduced by climate change, forest agencies will have to consider intensive strategies to maintain productivity. For example, they could undertake reforestation on a more massive scale than now practiced and possibly introduce subtropical species into the Southeast.

- A coordinated public and private reforestation effort, together with development of new and adapted silvicultural practices, would also be required. Forests are major carbon sinks, so a large reforestation program would also reduce atmospheric CO_2 concentrations, slowing the rate of global warming. This study did not evaluate the effectiveness of reforestation efforts.

EXTENT AND VALUE OF U.S. FORESTS

Forests occupy 33% of the U.S. land area and exist on some lands in all 50 states. In total, they occupy 298 million hectares (738 million acres) and are rich in such resources as water and wildlife.

Many biotic and abiotic factors influence the condition of forests, but climate is the dominant factor (Spurr and Barnes, 1980). This chapter summarizes the current knowledge and predictions concerning the effects of rapid climate change on U.S. forests.

Distribution and Ownership

Eight major forest regions of the conterminous 48 states contain 84% of the forested ecosystems of the United States (Figure 5-1). The forested areas of

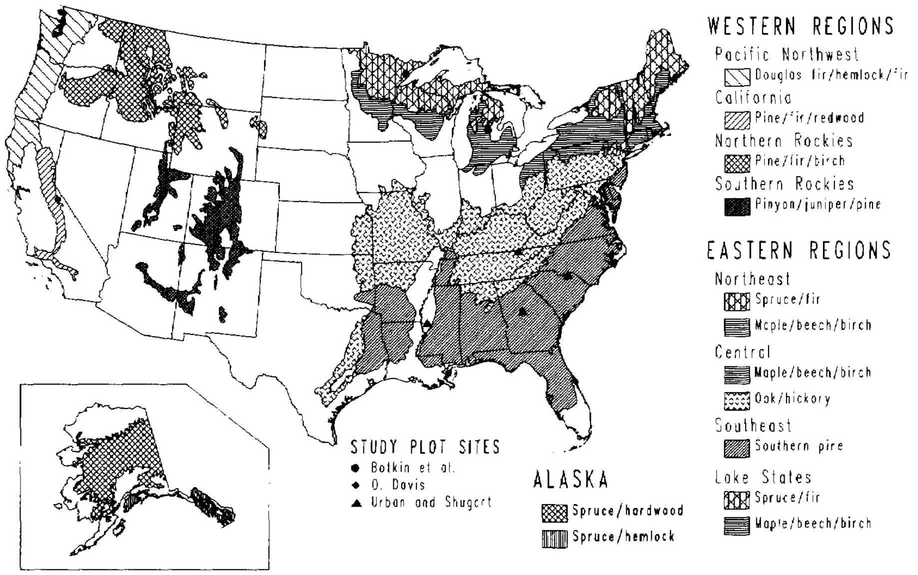


Figure 5-1. Major forest regions of the United States and their primary tree groups.

Table 5-1. Area of U.S. Forest Lands in 1977 by Federal, State, Private, and Other Ownerships (millions of hectares)[a]

	Regions/States	Primary Tree Species	Commercial Forests[b]				Other[c]	Total	% Total
			Federal	State	Private				
					Industry	Non-industry			
East	Northeast - CT, MA, ME, NH, RI, VT	spruce - fir - maple beech - birch	0.3	0.4	3.9	7.8	0.7	13.1	4.4
	Lake States - MI, MN, WI, ND, SE (E)	spruce - fir - maple beech - birch	2.3	2.8	1.7	9.9	4.2	20.9	7.0
	Central - DE, IA, IL, IN, KA, KY,	maple - beech - birch oak - hickory	1.8	2.0	8.6	22.9	2.6	37.9	12.7
	Southeast - AL, AR, FL, GA, LA, MS,	loblolly, shortleaf slash pine	5.8	1.0	14.7	54.3	8.0	83.8	28.1
West	Northern Rockies - ID, MT, SD(W), WY	pine - fir - birch	9.1	0.6	0.8	2.7	9.3	22.5	7.6
	Southern Rockies - AZ, CO, NM, NV, UT	pinyon - juniper - pine	6.4	0.3	0.0	2.4	24.1	33.2	11.1
	Pacific Northwest - OR, WA	D. fir - hemlock - fir	7.8	1.2	4.0	3.2	5.3	21.5	7.2
	California - CA	pine - fir - redwood	3.4	0.03	1.1	2.0	9.8	16.3	5.4
Separate States	Alaska - AK	spruce - hemlock - hardwood	3.3	1.0	0.0	0.1	43.9	48.3	16.2
	Hawaii - HI	ohia	0.01	0.2	0.0	0.2	0.4	0.8	0.3
		Total	40.2	9.5	34.8	105.5	108.3	298.3	
		% Total	13.5	3.1	11.7	35.4	36.3	100	100

[a] Hectare x 2.47 = acres.

[b] Commercial forests are those capable of growing at least 1.4 cubic meters per hectare per year (20 cubic feet per acre per year) of industrial wood materials.

[c] Other forests include county and municipal forests and those federal lands withdrawn from industrial and wood production for use as parks, preserves, and wilderness.

Source: USDA (1982).

16% (Table 5-1). Each forest region includes one or more forest types distinguished by the major tree species present. As a general rule, some types in each region have predominantly coniferous tree species (i.e., evergreen, needle-leaved, and softwoods); other forest types are composed mostly of deciduous trees (i.e., tree species that are broadleaved, have no winter foliage, and are hardwoods). Forest types with a mix of coniferous and deciduous trees, however, are not uncommon.

Superimposed over the natural distribution of trees, forests, and ecosystems in the United States is the human infrastructure. Ownerships include federal, state, and private lands (Table 5-1). Within the forests classified as "commercial" (64% of 298 million hectares), the federal government ownership of 40 million hectares (99 million acres) is primarily in the national forest system managed by the U.S. Department of Agriculture's Forest Service (36 million hectares or 91 million acres); most of the remainder is managed by the Department of Interior's Park Service, Fish and Wildlife Service, or Bureaus of Land Management and Indian Affairs. State ownerships total 9 million hectares (23 million acres). Private lands are divided between those of industrial forest companies (35 million hectares or 86 million acres) and those of small, private landowners, who collectively have 106 million hectares (262 million acres) (USDA, 1982).

Another significant segment of American forests consists of those maintained within urban and suburban areas. Examples are community parks, greenbelts, roadside forests, and wooded residential and industrial zones (USDA, 1981). These forest areas are important sources of outdoor recreation, wildlife habitat, and real estate values. In total, the urban/suburban forests of the United States occupy approximately 28 million hectares (69 million acres) (Grey and Deneke, 1978).

To the degree that all forest lands are owned by some individual or organization, all forest lands are under some form of management. A continuum of management policies exists, ranging from lands intended to have minimal human intervention except for protection from catastrophic wildfire (e.g., some parks and most wilderness areas) to lands where silvicultural practices are intensively applied (e.g., the most productive federal, state, and industrial forest lands dedicated to growing tree crops); (Table 5-2).

These forests under government and industrial management constitute roughly one-fourth of the total and might be the easiest to manage under climatic impacts simply because they are larger blocks of lands already under strong management commitments.

Value of U.S. Forests

Most populated regions in the United States are located close to or within a forested region. For instance, the Boston-Washington corridor is within the eastern hardwoods. The populations of Atlanta and the Southeast are interspersed among the southern pine forests. Chicago and nearby Great Lakes communities are surrounded by the mixed conifer-hardwood forests of that region, and the Los Angeles to San Francisco populations parallel the Sierra Nevadas to the east. In addition, urban/suburban forests exist in or near most of the nation's cities. Forests, therefore, are part of the environmental fabric and general habitability for the majority of U.S. citizens.

All forests shed water to some degree, and two thirds of the water runoff in the contiguous 48 states comes from forested ecosystems. Precipitation passes through forested ecosystems as canopy throughfall or flows along tree stems, and then flows along the ground surface or into the soil; eventually, some of the water flows into streams. Water yields from U.S. forests provide about 750 billion liters (200 billion gallons) of water each day for major uses such as irrigation, electricity production, manufacturing, and domestic consumption. These levels of demand are projected to continue to the year 2030 (USDA, 1981).

Table 5-2. Percentage of Forest Lands by Level of Management within Four U.S. Regions (estimates for 1977)

U.S. regions	Forest plantations[a]	Other commercial[b]	Reserved/deferred[c]
East			
North	9	80	11
South	21	69	10
West			
Rocky Mountains	2	38	60
Pacific Coast	16	44	40

[a] Intensively managed populations.
[b] Moderately managed forests.
[c] Recreational and protected forests

Source: USDA (1982).

A favorite use of forests is outdoor recreation. Activities include hiking, camping, hunting, sightseeing, boating, swimming, fishing, skiing, sledding, and snowmobiling. A 1977 survey of U.S. households indicated that a majority of people participated in outdoor recreation four or more times each year (USDA, 1981).

About 190 million hectares (470 million acres), or 64% of the total U.S. forested ecosystems, are highly productive commercial forest lands. These lands represent about 10% of the world's forest area, but they supplied nearly a quarter of the world's industrial forest products in the late 1970s (USDA, 1982). In 1980, 1.7 million people were employed in timber-based occupations across the United States. Such employment is basic to the economic well-being of many small towns and communities (Schallau, 1988). The total value of timber products harvested in 1972 was about $6.4 billion, and the total value after such processes as manufacturing, marketing, transport, and construction amounted to $48 billion, or 4% of the nation's gross national product. In 1979, timber product exports and imports were valued at $7 billion and $9 billion, respectively. Looking ahead, the consumption of wood products in the United States is projected to increase between current levels and the year 2030 (USDA, 1982).

RELATIONSHIP BETWEEN FORESTS AND CLIMATE

Scientific understanding of forest ecosystems has greatly advanced with each decade of this century. Yet the literature contains little information concerning the direct or indirect effects of climate change on the complex biological and physical processes in forest ecosystems. Some insights are gained from paleobotanical studies of past rates and magnitudes of ecological change during glacial-interglacial cycles, as well as changes in the species composition of forested ecosystems. Similarly, observations of forest responses to unusual drought or other weather extremes provide some knowledge. Estimates of rate, magnitude, and quality of change have also been derived using computer models developed by plant ecologists or forest management scientists for other objectives. Their validation for understanding how a forest can adapt to climate change is only in the initial stages.

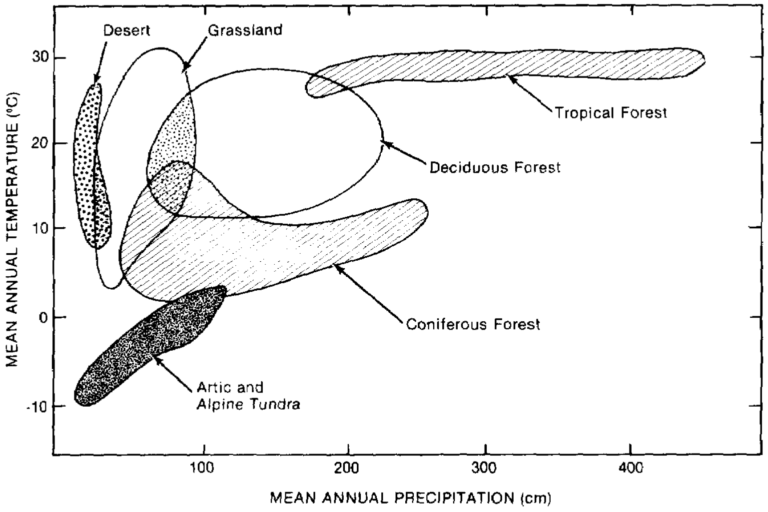


Figure 5-2. Approximate distributions of the major groups of world biomass based upon mean annual temperatures and precipitation (Hammond, 1972).

Climate is a primary determinant of existing forests. The ranges of annual average temperature and rainfall variation determine global forest distributions relative to different biotic regions (Figure 5-2). Substantial increases in temperature or decreases in rainfall could, for example, produce a shift from a forest to a grassland type. Thus, accelerated climate change resulting from human activities and related effects on U.S. forests is of high concern to citizens and policymakers alike.

Magnitude

Vegetation has been in an almost constant state of distributional change and adjustment due to an almost constantly changing climate over the past 10,000 years and even over the past several hundred years (Spurr and Barnes, 1980). Lines of evidence come from studies of fossils, tree rings, carbon-14 dating, plus peat and pollen analyses (Webb, 1987).

Historical climate changes appear to have been associated with such phenomena as fluctuations in solar radiation, earth orbit variations, and volcanic activity. Evidence of repeated continental glacial advances and contractions in the Northern Hemisphere dramatically illustrates the large-scale effects of global climate change.

In response to the glaciation, species shifted south. Evidence from fossil pollen, for example, indicates a southward shift of spruce into Georgia and east Texas during the last glacial advance and treeless tundra in the Great Lakes region (Spurr and Barnes, 1980). During the maximum interglacial warmth of 6,000 to 9,000 years ago, which was 1.5°C (2.7°F) warmer than the present temperature level, plant zones were one to several hundred kilometers (60 to 250 miles) north of present distributions.

Rates

All forested ecosystems experience change on both spatial and temporal scales; each biological and physical forest component may respond to climatic variation on different spatial and temporal scales. For example, microorganisms, insects, and birds come and go with relatively short-term climatic variation; shrub species' abundances vary within the timespan of decades; trees, once established, could persist for centuries. This understanding is important from the perspective of climate change, since it implies that forested ecosystems do not respond as a unit, but in terms of parts. Different parts respond differently; consequently, future forested ecosystems under a rapidly changing climate could be quite different from those existing today.

At the expected rapid rate of climate change, the potential rates of forest migration would become a major concern. Migration rates vary by species. Paleorecords of the Holocene (10,000 years ago to present) show that extension of ranges for tree species of eastern North American (in response to glacial retreat) varied from 10 to 20 kilometers (6 to 12 miles) per century for chestnut, beech, maple, and balsam fir (Zabinski and Davis, Volume D). Other species within the oak and pine groups extended at faster rates, i.e., 30 to 40 kilometers (19 to 25 miles) per century. It should be noted that there is some uncertainty as to whether these migration rates were in response to glacial retreat plus climate warming or primarily warming alone.

Mechanisms

Knowledge of causal links between weather patterns and forest response is fundamental to projecting growth and composition effects resulting from climate change. Another requirement is to understand the climatic influences on processes influencing populations of forest plants and animals. These include such phenomena as fires, windstorms, landslides, pest outbreaks, and other disturbances that affect survival and subsequent colonization by different species. Furthermore, the processes that control the dispersal of seeds through a mosaic of different ecosystem types (such as forest patches interspersed with agricultural lands, wetlands, grasslands, and other land-use groups) must be clearly defined.

Among the important factors now known to influence the growth and distribution of forests are the following.

Temperature

The optimum temperature for growth depends upon the tree species and other conditions. Warmer temperatures usually increase the growth of plants. However, high temperatures can decrease the growth of plants or cause mortality where temperatures greatly exceed optimum ranges for growth. Cold temperatures can limit plant distributions by simply limiting growth at critical stages or by directly killing plants.

Precipitation

Too much or too little precipitation can limit forest production and survival. Too much rainfall in some areas can cause flooding or raise the water table, thus drowning roots by reducing soil air that contains oxygen required for respiration or by promoting fungal attack. Too little rainfall can reduce growth, cause susceptibility to fire or pestilence, and possibly kill plants. The seasonal timing of rainfall is more important than total annual rainfall, although forests also require some minimum total annual rainfall (see Figure 5-2).

CO_2 Concentration

High CO_2 concentrations could increase tree growth through increases in photosynthesis rates and water-use efficiency (primarily hardwood species) when water and other nutrients are not limited (Strain and Cure, 1985). Plant responses to CO_2 have been investigated largely in growth chambers and are difficult to extrapolate to the real world. Responses are varied and do indicate some measure of adaptive capability most likely imparted from ancestral exposure to much higher and lower levels in the geologic past. However, in natural situations, water nutrients or temperature usually are limiting factors in forest growth, thus making the impacts of CO_2 enrichment uncertain. If water use efficiency increases, then tolerance to drought might increase, ameliorating declines in southern parts of ranges. Unfortunately, the current state of knowledge does not allow generalizations on this subject.

Another important relationship between forests and CO_2 is the role forests play as carbon sinks. Globally, forest vegetation and supporting soil contain about 60% of the organic carbon stored on world land surfaces. This organic carbon is largely cycled between forest ecosystems and the atmosphere by photosynthesis (uptake of CO_2) and respiration (CO_2 release) in the plants (Waring and Schlesinger, Ri5). Anthropogenically caused reductions of forests either directly (e.g., urbanization, mismanagement) or indirectly (as a response to CO_2 induced global warming) would tend to increase the "greenhouse effect."

The amount of sunlight bathing an ecosystem sets the upper limit on net primary productivity. Thus, the tropics exhibit higher productivity than do the boreal regions. This potential productivity would, of course, be limited by other climatic effects such as drought, cold, heat, and natural disturbances, and by the time required for forests to shift into new ranges. The length of day exerts considerable control on physiological processes such as release from and onset of dormancy. Significant northward shifts of forests would alter their day-length regime, producing uncertain results.

Nutrient Status

In addition to climate, most forest growth is strongly influenced by availability of soil nutrients. Disturbances over vast regions, such as drought followed by fire, can release large quantities of essential nutrients into the atmosphere or into surface waters. This leaves soils nutrient deficient. Lengthy periods of soil development are usually required to replenish the soil nutrients before a large, mature forest stand can be supported. In turn, soils reflect properties of the forests that they support. This results from decades of nutrient uptake, litterfall, decomposition, and other processes.

Atmospheric Chemistry

Much of the nutrient budget of forests involves deposition of chemicals from the atmosphere as gases, aerosols, or particles, or in solution with water as precipitation. Although most of these act as nutrients, some produce acid deposition that can leach important soil nutrients (e.g., $SO_4^=$), produce a fertilizing effect (e.g., NO_3), or damage leaf tissue (e.g., O_3). Climate change will alter transport paths of air pollutants, and increased temperature could increase the rates at which gases convert to deleterious forms.

Disturbances

Almost continually, forests experience natural disturbances or stresses from biotic or abiotic agents alone or in combination. Examples are insect and disease outbreaks, plant competition, wildfire, drought, cold extremes, and windstorms.

These disturbances, which are among the primary factors controlling the successional processes in forests (Pickett and White, 1985), may range from an opening of small gaps in the canopy as the result of single tree death or of windthrow occurring when trees are blown down by heavy winds (predominant successional mechanisms in eastern hardwoods) to large clearings from fire, windthrow, or pestilence (predominant successional mechanisms in western forests).

Landscape Processes

The horizontal movements of materials such as soil and biological organisms, together with human disturbances across the landscape, are critical to processes controlling tree migration, species diversity in forests, and the spread of fire, windthrow, and pestilence effects. These processes are very poorly understood; quantification in the emerging field of landscape ecology is just beginning.

Multiple Stresses

In general, trees or forests stressed by one factor, e.g., accelerated climate change, are more susceptible to natural stresses (secondary disturbances) such as insects, disease, or invading weed species. The concept of multiple stresses leading to forest declines is becoming more widely recognized (Manion, 1981). Regional climate changes, even if temporary, frequently predispose forests to damage by other natural or anthropogenic stresses.

PREVIOUS STUDIES ON THE NATIONAL EFFECTS OF CLIMATE CHANGE ON FORESTS

Concern regarding effects of climate change on U.S. forests has prompted several excellent reviews. One of the most comprehensive (Shands and Hoffman, 1987) was the result of a conference sponsored by EPA, the National Forest Products Association, and the Society of American Foresters. While pointing out the high uncertainty associated with current predictions of climate change, several authors suggested that if predictions are true, distributions of key forest species in the United States will change significantly.

Other recently produced compilations broadly consider forest effects along with other impacts (e.g., those on agriculture, prairie land, and the Great Lakes) (White, 1985; Titus, 1986; Meo, 1987; Tirpak, 1987). These reviews are largely pioneering efforts and some overlap occurs, but each presents some key points.

The methods used in the previous studies are quite similar to those used in this report. They include computer modeling of forest processes, literature surveys, studies of fossil evidence, and empirical relationships constructed by experts. The estimates of future change produced from these studies are generally based on the output of one or more of the general circulation models (GCMs) used for this report. Thus, the results of the previous studies are consistent with those reported here.

STUDIES IN THIS REPORT

Six studies on forest effects contributed to the regional case studies reported in this volume. The purpose was to use existing data bases analyzed in new ways to estimate effects on U.S. forests from climate change scenarios. The selection of the six studies was based upon three criteria: use of established statistical methods; hypotheses testing concerning causal mechanisms; and selection of a mix of studies that complemented each other, such that the strengths in one approach might overcome the weaknesses of another.

This report focuses primarily on forests within the contiguous 48 states. It is worth noting, however, that the largest magnitude of warming is expected in the northern latitudes encompassing the boreal forest and other forest types in Alaska and Canada. Thus, these large forests could also be under significant risk from climate warming.

RESULTS OF FOREST STUDIES

Design of the Studies

Characteristics of the six studies are briefly listed in Table 5-3. With the exceptions of the

Table 5.3. Principal Investigators, Regional Focus, and Method of Approach for the Regional Forested Ecosystem Studies

Principal investigator	Region	Method
Overpeck and Bartlein	Eastern North America	Correlation and fossil studies
Urban and Shugart	Southeast Uplands	Forest dynamic model
Botkin et al	Great Lakes	Forest dynamic model
Zabinski and M. Davis	California	Correlation
O. Davis	California	Fossil studies
Woodman et al	Southeast, California, and National	Literature review

Overpeck and Bartlein study and the Woodman study, the methods are discussed in the regional case study chapters and will be mentioned only briefly here. All of the forest studies are in Volume D.

Two studies used correlations between tree distributions and climate (Overpeck and Bartlein; Zabinski and Davis). Overpeck and Bartlein's approach consisted of correlating the modern pollen distributions of important tree species with January and July mean temperature and annual rainfall.

The correlation was then tested by reconstructing past pollen distributions from general circulation model simulations of past climates (during the most recent glacial-interglacial cycle) for each species and comparing them to observed pollen distributions from those periods. Future pollen distributions were then constructed from the expected doubled CO_2 climate projected from the different model climate scenarios. The correlations were constructed on modern pollen distributions, rather than tree distributions, to allow the direct comparison to fossil pollen data. Modern pollen distributions are similar to, but not exactly the same as, modern tree distributions. The verification studies indicated that the approach works reasonably well at a coarse spatial resolution. That is, northern trees are in the north and southern trees are in the south, with the regional patterns being reasonably well represented.

The approach of Zabinski and Davis was essentially the same as that of Overpeck and Bartlein, except that the correlations were constructed from the actual modern tree distributions rather than from the modern pollen distributions (see Chapter 15: Great Lakes).

Two of the studies used computer models of forest dynamics (Botkin et al.; Urban and Shugart). Growth characteristics of each tree species occurring in the study region are used by the models to determine the growth and development of individual trees on a site. These growth characteristics include such attributes as maximum age, maximum height, maximum diameter, and ranges in tolerance to stresses of temperature, moisture, and shade. Both studies explored forest response starting with bare ground on a range of soil types from well drained to poorly drained. Forest growth simulations from bare ground represent conditions after a fire, logging, or similar disturbance. Mature stand simulations are useful for investigating the potential response of present forests to gradual climate change in the immediate future.

For the California case study, Davis reconstructed vegetation patterns in the Sierra Nevadas from fossil pollen studies for the interglacial warm periods that occurred between about 6,000 and 9,000 years ago. These reconstructions represent possible analogs of a future warm period at the lower magnitude of the predicted future warming.

Woodman conducted a literature review for the Southeast and California forested regions and peripherally for the entire nation. The purpose was to ascertain the attributes of the forest resource in terms of extent, ownership, economic and recreational value, and policy considerations.

Limitations

Although predicted effects vary, these six analytical studies have results that are collectively consistent enough to advance our knowledge and justify concern regarding the future of U.S. forests under rapid climate change. The range of predicted effects is large; however, uncertainties exist regarding (1) the climate scenarios; (2) the kind and rates of responses of individual tree species; and (3) changes in forested ecosystems as a whole resulting from environmental change. All of these factors significantly influence the precision and accuracy of the results.

A major uncertainty in the simulation model approach involves the rates of species dispersal into a region. The current generation of models has no dispersal mechanisms. A species is simply present or it is not present. For example, Botkin et al. excluded most southern tree species so that their dispersal was unrealistically nonexistent, and these southern species could never enter the Great Lakes region. But if they had been included in the simulations, these species would have entered the northern forests at the same rate as the climate change. This would have assumed dispersal rates far in excess of reality. This limitation can, in part, be overcome by studies, such as those of Zabinski and Davis, that provide some insight into actual dispersal rates and species migration. The simulations did not consider the impact of transplanting southern species in these areas.

The timing of forest declines as estimated by the models should be interpreted with caution. Declines are triggered by periods of high environmental stress. Forest models are usually not operated far beyond current conditions, such as for extremely dry soils. Therefore, the extreme climate simulated by these models may not estimate the timing and behavior of forest declines as accurately as desired. It should also be remembered that there is much uncertainty concerning the rate and timing of the climate change itself.

A further cautionary point is that although the models considered temperature limitations, nutrient deficiencies, and soil moisture stress, other important factors might affect the timing and magnitude of tree responses. Examples of factors in need of consideration include disturbance effects (e.g., impacts from wildfires, pests, and pathogens), age-dependent differences in tree sensitivities to stress (e.g., older trees are often more susceptible), and potential CO_2 induced increases in water-use efficiency.

The models also carry assumptions about the environmental controls of species limits. In most cases these assumptions are reasonable, given that indices of environmental stress, such as July temperature or annual rainfall, are usually related to factors that more directly affect plant growth, such as accumulated warmth or summer drought. However, large uncertainties exist in some instances. This is particularly true with regard to the climatic controls of the southern limits of southeastern forests, simply because of their association with the continental margin. Does the climate at that latitude represent the actual climatic limitation to the distributions, or are the species simply stopped by a geographic barrier? No one really knows. These uncertainties were partially addressed by Overpeck and Bartlein, who compared their fossil pollen approach to the modeling approach. The two approaches use similar relations to climate, and both can be used reasonably well to simulate forest distributions in the geologic past.

Several uncertainties with the pollen-climate correlation approach limit its precision and accuracy. First, many of the plant taxa used in the study are plant genera (e.g., pine, oak) rather than species, and thus the simulated results are not taxonomically precise. Second, the results are applicable only on a regional scale; local scale predictions are not made. Third, and very significant, the simulated results assume that all the plants are in equilibrium with the new climate. Rates of dispersal vary between species, and several hundred years may pass before plant communities are again in equilibrium with climate. How this lag would affect plant community dynamics is not addressed in this study and is an important research question.

The paleoecological analysis of the past vegetation in the Sierra Nevadas (O. Davis) presents several uncertainties. First, differences with respect to weather variations (i.e., season to season and year to year) could produce strikingly different types of vegetation. Also, there is much uncertainty about what the most appropriate analog period might be -- or if one even exists. Furthermore, the rate of climate change in the future is predicted to be much faster than the rate of climate change during the past 20,000 years. Lags in the response of species to the future climate could strongly affect the type of forest at any one location, whereas in the past, with a more slowly varying climate, lags in species response were not as important in determining forest composition.

All of the studies are deficient in some very important processes controlling forest responses to climate, particularly disturbance regimes such as fires, windstorms, hurricanes, landslides, and pest outbreaks. Over some forest areas, periods of cloud cover could change. This is an important uncertainty, for if the annual total is significantly increased, reductions in solar radiation could mean reduced photosynthesis and thus less forest growth.

In addition, the responses of mature trees to elevated CO_2 under conditions of moisture, temperature, or other nutrient limitations remain largely unexplored. Most research on elevated CO_2 on trees has been performed in controlled chambers using seedlings, and results show an increase in photosynthesis and improved water-use efficiency in some cases (Strain and Cure, 1985). However, the seedlings were not previously grown in or acclimatized to high CO_2 environments. Evidence has shown that plants grown under high CO_2 will respond differently to changes in temperature, light, and moisture conditions (Strain and Cure, 1985).

Another shortcoming is that methods to extrapolate CO_2 fertilization results from laboratory experiments to the natural world are limited, and an understanding of regional changes in water-use efficiency is even more limited. Furthermore, complex interactions between fertilization effects and changes in water-use efficiency can produce unexpected problems such as increased heat loads due to effects on evaporation cooling. These interactions are not well understood but could produce major regional changes in forest responses. Therefore, it is not yet possible to quantitatively incorporate the direct effects of CO_2 on forests into studies such as these. Further, if water or nutrients are limiting to forest growth, they would likely exceed the fertilization effects of elevated CO_2. Also, forest canopies at optimum development have multilayered leaf areas so that light limitations exist for the lower portion of the foliage in addition to frequent water and nutrient limitations. This adds further weight to the belief that CO_2 enrichment may not significantly affect forest prod3uctivity.

Results

The six studies conducted for EPA consistently indicate that climate changes would significantly affect the natural forests of the United States. The distribution of healthy forests in the eastern United States appears to become greatly reduced from their present areas during the next century (Figures 5-3 and 5-4). This results from a very slow northward migration coupled with a fairly rapid decline in the southern and western parts of species ranges. Drier forest conditions in the United States, induced as much by increased temperature as by changes in rainfall, would mean less tree growth and therefore reduced forest productivity in general.

The forest simulation models provide an indication of the importance of uncertainties imparted by the climate scenarios. The climate scenarios differ primarily in their representation of regional rainfall patterns. The model results indicate that temperature has a large effect on forest health, either directly through cold and heat stress or indirectly through exaggerated drought effects. Thus, the overall characteristics of forest responses are remarkably similar among the three climate scenarios. However, this generalization is uncertain because models usually do not incorporate all possible mechanisms of impact.

Magnitude

Eastern Forests - Northern Limits

All of the study results suggest a northward expansion of most eastern tree species (Figure 5-3 displays results from Overpeck and Bartlein). That is, spruce, northern pine, and northern hardwood species would move north by about 600-700 kilometers (375-440 miles) into the Hudson Bay region of the Canadian boreal forest (Overpeck and Bartlein; Zabinski and Davis). New England coniferous forests would be replaced by more hardwood forests and especially by the oak species from the eastern mid-United States (Botkin et al.; Overpeck and Bartlein; Zabinski and Davis). As the northern mixed forests shift from spruce-fir to sugar maple, some sites could actually triple their present productivity (Botkin et al.).

Additionally, southern pine species could shift about 500 kilometers (310 miles) into the present hardwood forest lands of eastern Pennsylvania and New Jersey (Overpeck and Bartlein; Urban and Shugart; Solomon and West, 1986; Miller et al., 1987). Depending upon the severity of climate change, Urban and Shugart estimated that near the northern limits of slash pine in East Tennessee, aboveground woody biomass in 100 years could range from little change to an extremely low biomass with almost no trees (i.e., a grassland, savanna, or scrub). However, even with little decrease in productivity, species shifts would alter the forest composition from shortleaf to loblolly pine, a more commercially valuable tree species.

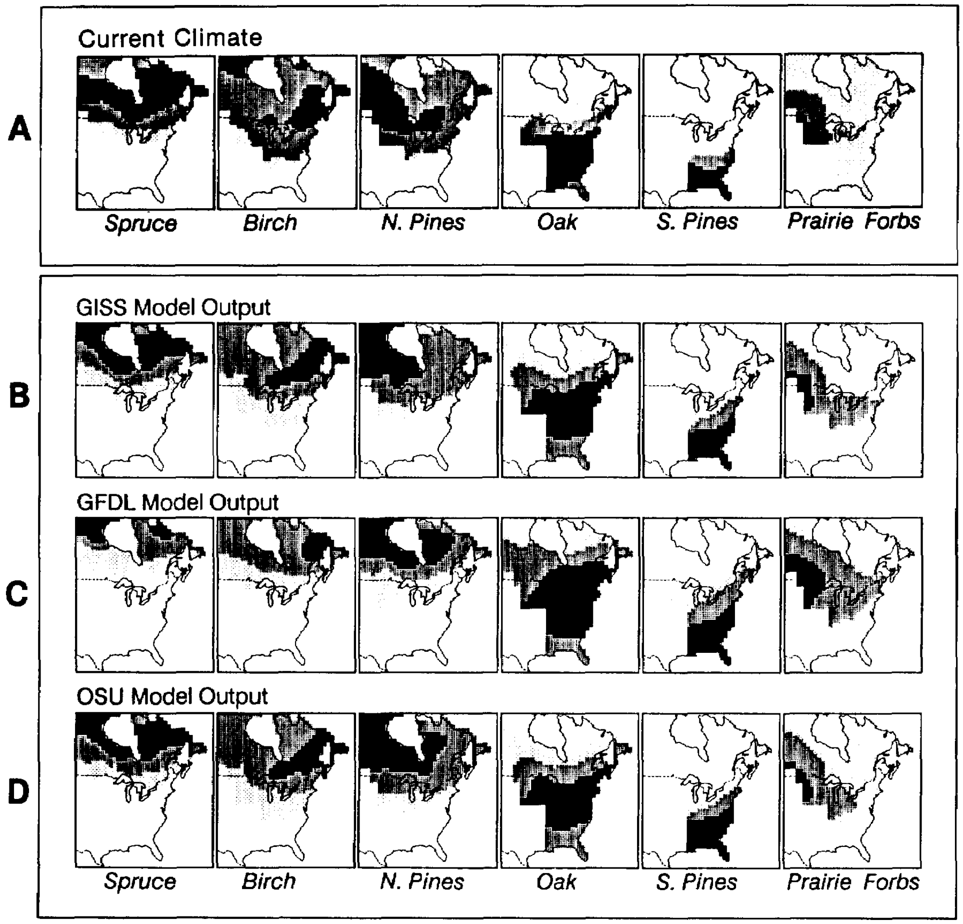


Figure 5-3. Maps of eastern North America depicting present distributions of major forest genera and herbacious vegetation compared with potential future distributions after reaching equilibrium with the climate predicted for doubled CO_2. The comparison is based upon (A) simulations using modern pollen data and simulated future pollen abundances for each of the three doubled CO_2 scenarios: (B) GISS; (C) GFDL; and (D) OSU. The three levels of shading in each scenario map indicate estimated future pollen abundances ranging from 20% (darkest or strongest chance of future distributions) to 5% and 1% (lightest or least chance of future distributions) (Overpeck and Bartlein, Volume D).

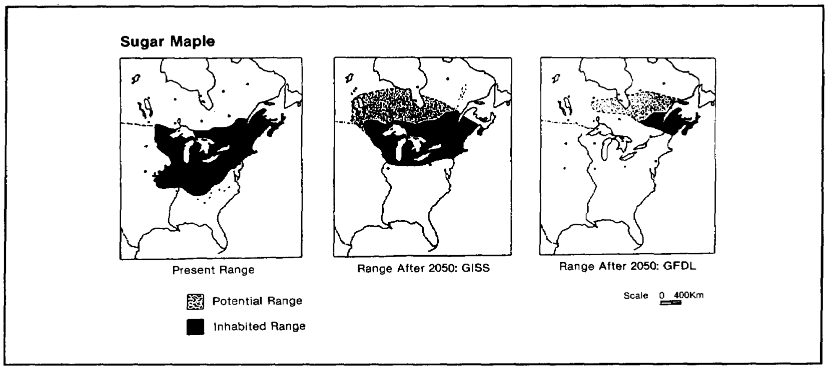


Figure 5-4. Present and future geographical range for sugar maple (Zabinski and Davis, Volume D).

Eastern Forests - Southern Limits

Ultimately, forest decline and mortality could truncate southern distributions of tree species by as much as 1,000 kilometers (625 miles) in many northern hardwood species (Zabinski and Davis; Overpeck and Bartlein) or by as little as a few hundred kilometers (about 120 miles) in southern pines and hardwoods (Urban and Shugart; Solomon and West, 1986). Under the driest scenario (GFDL), Zabinski and Davis estimate local extinction in the Great Lakes region of many eastern tree species such as eastern hemlock and sugar maple (Figures 5-3 and 5-4). These estimates bear considerable uncertainty for all species.

These uncertainties are particularly true for the southern limits of southeastern species that border the continental margin. The actual southern climatic limitations of these species are not well known (Urban and Shugart). Nevertheless, under the most severe climate scenario in the Southeast with increased temperatures and decreased growingseason precipitation, Urban and Shugart's results suggest that the 18 tree species they considered would no longer grow in the southern half of the region. Present forest lands in the region would be replaced by scrub, savanna, or sparse forest conditions. This estimation results from scenario conditions of heat that would exceed the tolerance limits for most tree species. Under the mildest scenario (OSU), even forest areas in South Carolina and southward would be marginal, supporting about half their current biomass.

Biomass accumulations in 100 years for mature natural forests in productive sites in the Great Lakes region could be reduced to 23-54% of their present values (Botkin et al.; Solomon and West, 1986). On poor sites, forests could be converted to grassland or savanna with very low productivity, ranging from 0.4 to 28% of their present values.

Western Forests

Similar projections were made for six western coniferous species: ponderosa and lodgepole pine, Douglas-fir, western hemlock, western larch, and Englemann spruce (Leverenz and Lev, 1987). Estimations are mixed for the West. Because of the mountainous conditions in the West, upslope shifts are possible for Douglas-fir, ponderosa pine, and western hemlock in the northern Rocky Mountains. In the coastal mountains of California and Oregon, Douglas-fir could shrink in the lowlands and be replaced by western pine species (O. Davis; Leverenz and Lev, 1987). Overall, the western forest lands are estimated to favor more drought-tolerant tree species, such as the hard pine group, at the expense of fir, hemlock, larch, and spruce species.

If regional drought persisted, the frequency of fires could increase, significantly reducing total forested area. Also, with massive upslope movement, some species could be pushed off the tops of mountains into local extinction.

No quantitative estimates have been derived for productivity for the western forests under potential warming conditions. However, using the analog approach of Davis, under the most severe conditions projected for California, the species composition of the west-side Sierra Nevada forests would become more similar to that of the east-side forests. This could reduce the standing biomass to about 60% of current levels.

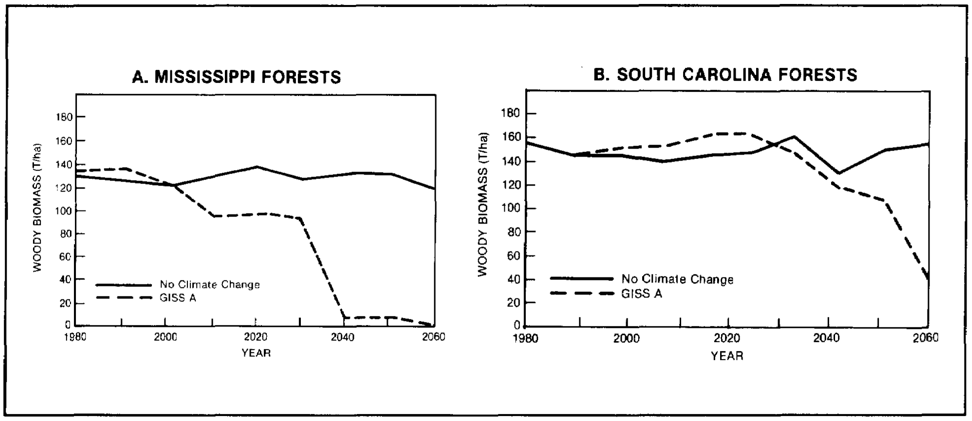


Figure 5-5. Estimated changes in biomass of mature forests in Mississippi (A) and South Carolina (B) under the GISS transient climate change scenario (Urban and Shugart, Volume B).

Rates of Decline and Migration

In the Great Lakes region, significant forest decline and forest compositional change could become evident within 30 to 60 years (Figure 5-5A; Botkin et al.). In the Southeast region, forest declines could become most evident in 60 to 80 years with declines in the drier western portions occurring even earlier, perhaps in about 30 years (Figure 5-5B and C); Urban and Shugart). As previously discussed in this chapter (see Limitations) there is considerable uncertainty about these numbers.

These rapid declines, coupled with the expected magnitude of climate change, raise the question of how fast forests can migrate. Based upon fossil records, Zabinski and Davis have estimated that the maximum dispersal rate of several tree species in response to the last glacial retreat was roughly 50 kilometers (30 miles) per century. Under the expected rapid warming, they estimated that a dispersal rate of about 1,000 kilometers (600 miles) per century would be required to maintain species distributions near their current extent. Such migration rates are doubtful, suggesting greater reductions in species ranges under rapid climate change, with declines in the drier western portions.

Mechanisms of Migration

Distribution changes (i.e., migrations) suggested by these studies must be considered carefully. Reproductive processes are essential for the migration of tree species across the landscape. For many tree species, climate change could reduce natural regeneration in an existing location and introduce the species at different latitudes or altitudes. Reproductive processes in trees, such as flowering, pollination, seed set, seed germination, and seedling competitive success, are particularly sensitive to climate.

Specific regional climate scenarios vary as a function of the GCM. All scenarios estimate increases in temperature; however, some include increases in rainfall, and others have decreases. The northward shifts of species appear to result from a release from cold temperature stress, which normally freezes flowers, seedlings, and even adult trees. However, the western and southern limits of eastern tree species appear to result from insufficient moisture and excessive heat stress, which primarily affect sensitive life history stages but can also affect mortality rates of adult trees. Though difficult to detect in the early phases of rapid climate change, tree mortality is sensitive to chronic moisture stress and mortality rates would likely increase among the major forest regions of the United States.

Two points are important about regional uncertainties of future rainfall distribution. First, changes in the seasonal distribution of rainfall are as or more important than relatively small changes in the annual total. If summer rainfall decreases while winter rainfall increases, the trees may still experience summer drought stress. Second, evapotranspiration is a log function of temperature. Therefore, as temperature goes up, water loss from trees and soils can increase tremendously. If minor increases in rainfall are not sufficient to override the evapotranspirational losses of water, drought impacts will pervade. Both of these mechanisms appear to dominate the forest impacts in this study.

All of the study approaches used under all of the climatic scenarios estimate major forest declines in the southern parts of species ranges and expansions to the north. These declines, resulting primarily from drought stress, would occur despite the differing rainfall predictions among the climate scenarios used in this study. Global precipitation is generally projected to increase slightly with global warming (see Chapter 4: Methodology), but it is not known whether this increase would be sufficient to compensate for potential increases in plant moisture stress caused by higher temperatures. Precipitation in some regions may decline. Droughts would become more common. The western limits of eastern forests could similarly retract as the climate warms.

Existing forests probably would not shift intact, but would change in composition. Variations in migration rates and sensitivities to weather variables produce individual responses to climate change. These changes are consistent with the well-known dynamic nature of ecosystems and were projected for the forests of all regions. In the Great Lakes region, for example, beech could decrease in abundance (Zabinski and Davis), and birch and maple could increase (Botkin et al.). On some lands, forest productivity could remain about the same as today, but changes to less economically important species could be significant.

Not considered quantitatively in any of the studies are changes in forest disturbance regimes. These changes should not be considered lightly. Extreme and more frequent climatic variations (see Chapter 3: Variability) could cause much higher mortality in U.S. forests than the current experience. Although little is known as yet, some locations may experience an increase in the frequency of extreme weather events, for example, wind, ice, or snow storms, droughts, and flooding. Besides the direct damage these events can cause, they can predispose forests to damage from secondary stresses such as insects, disease, and wildfires.

ECOLOGICAL AND SOCIOECONOMIC IMPLICATIONS

The effects of doubled CO_2 climate changes may be considered from two perspectives: ecological and socioeconomic. Evidence for significant national implications is strong from both viewpoints.

Ecological Implications

Ecological implications for forests commonly start with tree response. But strong implications also exist for other ecosystem components, e.g., animals, soils, water, secondary impacts, and as noted, the atmosphere through which climate change is mediated. Forest effects are described in terms of tree distribution changes and biomass production changes, but many other processes interact among the other major components. Thus, significant changes in tree response would be accompanied by ecological reverberations throughout all the forested areas of major U.S. regions.

Tree Distributions and Biomass Productivity

As discussed, migrations of forest tree species to the North in response to rapid warming in North America during the next century will be likely.

However, significant lag is possible. Even under the maximum rates of species dispersal estimated by Zabinski and Davis, healthy forest areas may not redevelop for several centuries. Furthermore, if climate continues to change beyond the next century, then healthy forests may never redevelop. Meanwhile, distribution ranges may not be under such constraints, so the extent of healthy forested regions in the United States probably would be greatly reduced. Though some locations may have increased productive potential from a biomass per hectare standpoint, the large reductions in areas with healthy forests would likely create a net reduction in forest productivity for the United States for several centuries or longer.

Even if a massive reforestation effort were undertaken, the new forests resulting from species shifts might or might not be as productive as existing forests. More northern latitudes or higher elevations raise other considerations. Farther north, days are longer in the summer and shorter in the winter. At higher elevations, damaging ultraviolet light intensity is greater. All of these conditions could lower forest productivity below present levels. Furthermore, it is not clear that reforestation would be successful. A major intent of reforestation would be to artificially speed up northward migration of tree species. However, seedlings that would appear to be favored on some northern sites several decades in the future may not survive there now because of constraints imposed by temperature, day length, or soil conditions. Similarly, seedlings that could not survive on those sites now might not be the best adapted species for those same sites several decades in the future.

Animals

A change in the size and relative homogeneity of forests could influence whether some animals can continue to live in their present locations. Often, animals are finely adapted to habitats specific to a certain location. For some animals, migration can be hindered by boundaries between forests and other land types or facilitated as animals move along edges. Furthermore, some animals (e.g., many game species) prefer young forests, and others (e.g., many rare and endangered species) prefer old forests. In turn, animals can exert a profound influence on forest structure and composition through selective browsing of seedlings, insect attack of different tree species, seed dispersal, and other effects. All of these factors illustrate that climate change could influence the regional patterns of biotic diversity in both plants and animals (see Chapter 8: Biodiversity).

Soils

Soils under warmer climates also would change, although at a much slower rate than shifts in species distribution. Increased soil temperatures, however, would affect the entire range of physical, chemical, and biological soil processes and interactions. For example, populations of bacteria, fungi, and animals could increase in a way that would accelerate decomposition of litter and thereby reduce the availability of nutrients essential for forest growth (Spurr and Barnes, 1980).

Considerable time may be required to develop optimum soil conditions for high forest productivity supporting species at more northern latitudes or higher elevations. Furthermore, it is not at all clear how well some northern soils could support more southern species. The soils of the boreal forest differ from those under the deciduous forests to the south.

Water

Where forests give way to drier conditions (e.g., in the Great Lakes region and California), many lands now serving as watersheds might be used for different purposes. Furthermore, regional-scale disturbances (such as fire) and applications of chemicals (such as fertilizers and pesticides) could degrade regional water quality and increase airborne toxic chemicals (see Chapter 9: Water Resources).

Sea level rise may impact some coastal forests. Many forest lands of high value for timber production (e.g., in the Southeast) or recreation (in the Northeast, Northwest, and California) are close to ocean coasts. Inundations, decreases in depth to the water tables, and saltwater intrusions could trigger rapid forest declines near these areas.

Secondary Impacts

As the southern bounds of forests tend to shift north, forest decline (sick and dying trees) could become extreme over large areas that would become highly susceptible to weed competition, pest outbreaks, or wildfire. As forests decline, species of lower economic value, as well as weedy shrubs and herbs, could invade via wind dispersion. Under stressful environments, such species are severe competitors with most commercial tree species.

Trees experiencing less favorable growth conditions are more stressed and will be vulnerable to insect and disease attack. These secondary pest impacts could last "until the most vulnerable forest stands or tree species are eliminated" (Redden, 1987). In addition, it is estimated that the incidence of catastrophic wildfires will increase in U.S. forests with higher temperatures. Simand and Main (1987) estimated that fire occurrence and fire-suppression costs would increase 8 and 20%, respectively.

Socioeconomic Implications

The United States enjoys substantial economic and cultural benefits from its forests. Until recently, the nation's forest managers assumed that these benefits could be sustained by maintaining forests in a healthy condition (Fosberg, 1988). This was achieved, for example, by preventing fires or pest invasions, avoiding careless use, and enhancing productivity through good silviculture.

Beginning with the possibility of regional air pollution damage to forests, suspected in the 1980s, alterations of the environment external to forests presented a new concern. Research and policy discussions to deal with this issue are ongoing.

If climate changes as rapidly as predicted, this additional external influence with its more global dimensions looms as a possible hazard to forests and their use. As can be imagined, a list of potential socioeconomic concerns would be large. To provide a brief perspective, three issues are considered.

Quality of the Human Environment

The forest amenities enjoyed by most U.S. citizens will be affected according to different forest responses. In the Boston-Washington corridor, a composition change from predominantly hardwood to predominantly pine forests, though ecologically significant, may not be noticed by most people if it occurs gradually. However, a delay of years or decades between the decline of existing forests and replacement by migrating tree species would likely elicit a strong concern. In the Atlanta-Southeast region, the southern pine forests, while undergoing a gradual expansion of their northern boundaries, would have less vigor in the remaining stands. This could raise their vulnerability to damage from insects and disease, reducing esthetic values -atleast an intermediate impact for most of the local citizens. In contrast, within some portions of the Southeast, the Great Lake region, and California, drier climates may cause the loss of some forest lands to prairie or desert conditions -- a severe change for the people there, not only in their living environment but also in the whole spectrum of forest land use.

Recreation

Forests must be in a relatively healthy condition to support quality recreational use (Clawson, 1975). Forests undergoing gradual composition changes might remain healthy, but rapid changes would most likely cause stressed or declining forests. Such forest conditions would have less recreational appeal because of such factors as less pleasing appearance, greater threat of wildfire, and reduced hunting quality when game populations change or are diminished. Furthermore, drier conditions in U.S. forests would harm recreational opportunities that depend on abundant water or snow.

Wood Products

Altered U.S. forest productivity resulting from climate change would have obvious major economic impacts. Significant yield reductions could lead to unemployment, community instability, industrial dislocation, and increased net imports of wood products.

Reforestation projects could make up for some losses in forest productivity and artificially advance migrations forced by climate change. Reforestation technology has greatly improved in recent decades so that success rates also have increased greatly. Examples are high-vigor seedlings developed through improved nursery practices, genetic selection, and vegetative propagation. Improvements in the field include machine planting, fertilization, and weed control on selected sites. Results are evident from the large acreages of plantations established in the United States in recent decades, particularly with loblolly pine in the Southeast and Douglas-fir in the Pacific Northwest (Table 5-2). Large-scale reforestation in the United States and elsewhere could significantly add to the total carbon sink provided by world forests, thereby offsetting some of the buildup of atmospheric CO_2. Although this was not studied, attempts to reforest some very dry sites may be unsuccessful.

Innovative manufacturing trends should prove to be timely during times of rapid forest change. High-strength and durable products from reconstituted wood (e.g., new particle board concepts, warp-proof hardwood lumber, paper products of fiber from multispecies) are now in use or well along in development. These new methods will lessen the present overdependency on a few commercial conifer species from stands above minimum size and quantity (Ince, 1987). The result will be an ability to use the timber resources of the future, however they change in composition.

FOREST POLICY AND CLIMATE CHANGE

Historically, U.S. forest policies have undergone continued development to meet national change (Young, 1982). The earliest policies were adapted by the New England colonies in the 1600s to regulate overcutting near settlements. Wood was needed for fuel and buildings, but existing methods were not capable of long distance log transportation. Development of U.S. forest policies has continued and has been particularly intense this century, as the national forests, national parks, and wilderness areas have been established.

At present, forest managers are dealing with many additional policy issues. Five of these (Clawson, 1975) are important to climate change/forest response:

- How much U.S. land should be devoted to forests?
- How much forest land should be withdrawn from timber production and harvest?
- How should the federal forest lands be managed? (That is, the lands under the USDA Forest Service, USDI Park Service, Bureaus of Land Management and Indian Affairs, and other federal agencies that manage forest lands.)
- What constraints (e.g., mandatory forest practices) should be placed on forest managers to ensure national environmental goals?
- Who should pay the additional costs incurred in implementing new policies?

The large array of forest ownerships in the United States, public and private, makes development and implementation of forest policy more complicated than in most countries. Around the world, about 77% of all forests are in some form of public ownership (Hummel, 1984). The diversity of owners and managers results in widely divergent goals and objectives.

How Much Land Should Be Forested?

Changes in forest composition or regional boundaries induced by rapid climate change would magnify the complexity of national forest policy even further. Lands in forests now would require review relative to such competing needs as agriculture and residential use, which would also be adjusting to climate change.

How Much Should Be Withdrawn From Timber Production?

Where the productivity of wood is significantly reduced, increased, or shifted, a policy question that would surely arise concerns whether forest lands should be reallocated to maintain timber production. If so, how should competing forest uses, such as watersheds, parks, and wilderness, be treated? How much of each can the United States afford under changed climatic conditions? Should the federal government purchase more forest lands to support all public needs?

In the short term, forest managers could compensate for some loss of productivity by improved technology, although at increased costs. An example would be establishment of more drought-tolerant plantations through genetic selections, improved nursery stock, and more intensive silvicultural practices (e.g., weed control and thinning). Introducing new species adapted to warmer climates might be possible in some locations, but this would call for development of new silvicultural regimes and utilization methods -- possible, but time consuming and costly. In the long term, if growing conditions become extremely difficult on some U.S. forest lands because of climate changes, establishing trees for wood production on such sites may not be economically justified.

How Should We Manage Federal Forests?

The national forests under the USDA Forest Service are managed according to a series of complex legal directives and administrative procedures, beginning with the Organic Act of 1897 (Woodman and Furiness, Volume D). Ultimately, the objective became to manage the national forests for multiple uses, with timber and other forest resources on a sustained-yield basis and certain lands set aside as wilderness areas. The National Forest Management Act of the mid-1970s requires management plans for each national forest subject to public review. The plans look ahead 50 years and are to be updated every 10 years.

Lands managed by the Department of Interior are under similar mandates. For example, a congressional act passed in 1976 charged the Bureau of Land Management to manage its 2.3 million hectares (5.1 million acres) of forest and range land according to multiple-use and sustained-yield principles. Similarly, the National Park Service is mandated to manage national parks, monuments, historic sites, and so forth, for the recreational enjoyment of people. Such activities as timber harvesting, hunting, mining, and grazing are not permitted. In addition to the federal government, most states, many counties, and some municipalities own forest lands.

The Forest and Rangeland Renewable Resources Planning Act of 1974 requires the Secretary of Agriculture to make periodic reviews of the nation's forest and rangeland resources. In the future, these assessments and planning efforts should include consideration of the possible effects of predicted climate changes.

A key issue is the level of priority given to maintaining forest health under changed climate conditions. For instance, under more adverse environments, should national forests be left to decline as a natural process, thereby losing esthetic values in parks, water yields from watersheds, and highly productive timber crops? Or should silvicultural forest techniques such as thinning, weed control, fertilization, and reforestation be employed in an attempt to preserve them? This question and others will challenge the fundamental concepts of the benefits of multiple use and sustained yield of U.S. forests.

How Can We Ensure National Goals?

At the minimum, federal agencies must plan and act in concert with the state and private forest organizations. In the first half of this century, the federal government attempted to regulate forest harvests on all federal, state, and private lands. Development of this policy did not survive strong public concern and intense political debate against such policy (Worrell, 1970); the same sentiment would likely exist today. However, under the influence of climate change, the nation may once again have to face the touchy issue of what restraints or forest practices must be regulated for all public and private lands.

Solomon and West (1985) point out that while climate change might disrupt forest ecosystems in the future, it is uncertain whether forest managers could or would be able to apply silvicultural practices on a scale large enough to maintain the net productivity of commercial forest lands in the United States. Some states (e.g., Washington, Oregon, and California) have laws specifying fire protection requirements, control burn practices, and reforestation minimums following timber harvests. Zoning, permits, licenses, and various taxation measures also have been attempted with mixed results. It is much easier to prevent owners from destroying forests than to compel them to implement silvicultural practices.

Reforestation

To keep pace with the global climate changes estimated, the U.S. reforestation effort conceivably would need to be doubled or tripled in size. In recent years, about 800,000 hectares (2 million acres) per year (approximately 700+ million seedlings) have been reforested in the United States (USDA, 1982). Costs range from \$200 to \$700 per hectare (\$80 to \$280 per acre) depending upon species, site preparation, plantation density, and planting method. Using \$500 per hectare (\$200 per acre) as a mode, the total annual expenditure is near \$400 million. About 0.4% of the commercial land base is reforested annually. At this rate, it would take 100 years to reforest 40% of the U.S. forest lands, assuming no repeat hectares to cover failures or harvests of the first plantations.

An expansion on the scale suggested above would require large investments in seed procurement, tissue culture capability, nursery capacity, and research to improve knowledge about the establishment and silviculture of droughtresistant plantations. Even if the dollar commitments were made, reforestation at this scale might be possible only if all forest lands were managed by one organization. The complex forest ownership pattern in the United States, therefore, would be an issue to overcome in a national reforestation program.

Who Should Pay?

Adjusting forest policies to address the issues arising from climate change will most likely raise the costs of using the nation's forests -- whether for water, recreation, esthetics, or timber. Additional research to answer many new questions will also require more funds. A major question will be who should pay for these costs. Land owners? Forest users? Consumers? All taxpayers? The answers will come when better information is available on resulting forest effects, followed by public debate establishing new priorities for forest use in a changed climate.

RESEARCH NEEDS

The forest effects resulting from rapid climate change are at present hypothetical. The change has not yet occurred, and many uncertainties are associated with the predictions. Effective policies to deal with new forest effects will require more information and fewer uncertainties that must come through forest ecosystem research. Four broad questions concerning U.S. forests frame the research needs for the 1990s: What will the effects be? How can they be measured reliably? How should they be managed? How can we ensure that research will be conducted in a timely fashion?

Effects of Climate Change

What will be the effect on the nation's forest ecosystems if climate changes occur as predicted by the middle of the 21st century? While subsets of this question must include extent, magnitude, and risk considerations, additional knowledge is needed concerning the following:

1. Forest migration processes and rates, including the landscape processes that control the horizontal movements of forests, animals, and disturbances;

2. Interactions among the different landscape components and land-use practices that affect biodiversity, and water quantity and quality;

3. The impact of climate change alone and in combination with other natural or anthropogenic influences, such as insects, pathogens, CO_2 enhancement, air pollutants, UV-13 radiation, and acid deposition on U.S. forests; and

4. The processes and mechanisms that play key roles in forest ecosystem effects -- both biologically as in photosynthesis and respiration, and physically as in flows of energy, carbon, water, and nutrients through ecosystems.

Methods

How can forest ecosystems be measured to reliably detect the effects of rapid climate change? Today, the response of ecosystems to environmental change is largely based upon extrapolating from field observations, from knowledge about seedlings or individual trees of a small number of commercially valuable species, and from computer models. The following must be accomplished:

1. A determination of the most useful integrating variables for forest ecosystems that indicate the effects of climate change -- particularly variables that are earlywarning indicators of ecosystem response;

2. Effective sampling designs developed for experiments and long-term monitoring at the forest ecosystem scale; and

3. Improved models capable of projecting regional effects on forests across multiple spatial and temporal scales.

Forest Management

What options are available to the public and private forest managers and owners in the United States to address the changes in the nation's forests that might occur in the next century? Research is needed to accomplish the following:

1. Understand the socioeconomic impacts of all forest ecosystem effects to clarify economic risks and alternatives; and

2. Develop technology to mitigate the adverse effects or to exploit the benefits of forest

change, such as breeding, bioengineering, transplanting, fertilization, irrigation, and other management approaches.

Timing of Research

The timing of the research is critical. The effects of climate change may be some decades away, but this should not lessen the urgency to begin research toward better information and methods. The complexities of the science are very large. Developing a base of knowledge to identify potential forest changes before they are upon the nation will require significant time and resources.

REFERENCES

Barbour, M.G., J.H. Burk, and W.D. Pitts. 1987. Terrestrial Plant Ecology, 2nd Ed. Menlo Park, CA: Benjamin/Cummings Publishers.

Botkin, D.B. 1979. A grandfather clock down the staircase: stability and disturbance in natural ecosystems. In: Waring, R.H., ed. Proceedings of the 40th Annual Biological Colloquium. Forests: Fresh Perspectives From Ecosystem Analysis. Corvallis, OR: Oregon State University Press, pp. l10.

Clawson, M. 1975. Forests for Whom and for What? Resources for the Future. Baltimore, MD: Johns Hopkins University Press.

Cubbage, F.W., D.G. Hodges, and J.L. Regens. 1987. Economic implications of climate change impacts on forestry in the South. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Davis, M.D., and D.B. Botkin. 1985. Sensitivity of the cool-temperate forests and their pollen to rapid climatic change. Quaternary Research 23:327-340.

Fosberg, MA. 1988. Forest productivity and health in a changing atmospheric environment. In: Berger, A., et al., eds. Climate and Geosciences: A Challenge for Science and Society in the 21st Century. NATO ASI Series. Series C; Mathematical and Physical Sciences, Vol. 285. Dordrecht, The Netherlands: Kluwer Academic Publishers. pp.681-688.

Grey, G.W., and FJ. Deneke. 1978. Urban Forestry. New York: John Wiley and Sons.

Hammond, A.L. 1972. Ecosystem analysis: biome approach to environmental science. Science 175:4648.

Hedden, R. 1987. Impact of climate change on forest insect pests in the southern U.S. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Hummel, F.C., ed. 1984. Forest Policy, a Contribution to Resource Development. The Hague: Martinus Nijhoff/Dr. W. Junk, Publishers.

Ince, P.J. 1987. Technology, timber demand and timberland investment. In: A Clear Look at Timberland Investment, Milwaukee, WI; April 2729. Conference proceedings. Forest Products Research Society.

Lavdas, L.G. 1987. The impact of climate change on forest productivity. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Leverenz, J.W., and D.J. Lev. 1987. Effects of carbon dioxide-induced climate changes on the natural ranges of six major commercial tree species in the western United States. In: Shands, W.E., and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington, DC: Conservation Foundation, pp. 123-156.

Manion, P.D. 1981. Tree Disease Concepts. New Jersey: Prentice Hall.

Meo, M., ed. 1987. Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues; May 2829. New Orleans, LA: University of Oklahoma and U.S. Environmental Protection Agency.

Miller, F.W., P.M. Dougherty, and G.L. Switzer. 1987. Effect of rising carbon dioxide and potential climate change on loblolly pine distribution, growth, survival and productivity. In: Shands, W.E., and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S.

Forests. Washington, DC: Conservation Foundation, pp. 157-188.

Pickett, S.T.A., and P.S. White. 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Inc. Harcourt Brace Jovanovich.

Schallau, C.H. 1988. The forest products industry and community stability: the evolution of the issue. Montana Business Quarterly Summer: 1-8.

Shands, W.E., and J.S. Hoffman, eds. 1987. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington DC: Conservation Foundation.

Simand, AJ. and WA. Main. 1987. Global climate change: the potential for changes in wildland fire activity in the Southeast. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Solomon, A.M., and D.C. West. 1985. Potential responses of forests to CO_2 induced climate change. In: White, M.R., ed. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. DOE/ER-0236. pp. 1451709.

Solomon, A.M., and D.C. West. 1986. Atmospheric carbon dioxide change: agent of future forest growth or decline? In: Titus J.G., ed. Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 3: Climate Change. Washington, DC: U.S. Environmental Protection Agency.

Spurr, S.H., and B.V. Barnes. 1980. Forest Ecology, 3rd Ed. New York: John Wiley and Sons.

Strain, B.R., and J.D. Cure, eds. 1985. Direct Effect of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238.

Tirpak, D.A., ed. 1987. Potential Effects of Future Climate Changes on Forest and Vegetation, Agriculture, Water Resources and Human Health, Vol. V. Assessing the Risks of Trace Gases That Can Modify the Stratosphere. Washington, DC: U.S. Environmental Protection Agency. EPA 400/1 - 87/OO1E.

Titus, J.G., ed. 1986. Climate Change, Vol. 3. Effects of Changes in Stratospheric Ozone and Global Climate. Washington, DC: U.N. Environmental Program and U.S. Environmental Protection Agency.

USDA. 1981. U.S. Department of Agriculture, Forest Service. An Assessment of the Forest and Range Land Situation in the U.S. Forest Resource Report No. 22.

USDA. 1982. U.S. Department of Agriculture, Forest Service. An Analysis of the Timber Situation in the U.S. 1952-2030. Forest Resource Report No. 23.

Waring, R.H., and W.H. Schlesinger. 1985. Forest Ecosystems, Concepts and Management. Orlando, FL: Academic Press, Inc.

Webb, T. 1987. The appearance and disappearance of major vegetational assemblages: long-term vegetational dynamics in eastern North America. Vegetation 69:177-187.

White, M.R., ed. 1985. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. DOE/ER-0236.

Worrell, A.C. 1970. Principles of Forest Policy. New York: McGraw-Hill.

Young, R.A., ed. 1982. Introduction to Forest Science. New York: John Wiley and Sons.

CHAPTER 6
AGRICULTURE

FINDINGS

Climate change would affect crop yields and result in northward shifts in cultivated land, causing significant regional dislocations in agriculture with associated impacts on regional economies. It would expand crop irrigation requirements, stress livestock production, and increase infestations of agricultural pests and diseases. Preliminary results suggest that although U.S. crop production could decline, supplies would be adequate to meet domestic needs. The potential for reduction of the national agricultural capacity and the many uncertainties surrounding the interactive effects on the agricultural system create the necessity to respond to the climate change issue.

above temperature thresholds for particular crops in some locations. The exact magnitude of change will be sensitive to changes in climatic variability, particularly the frequency of droughts.

Crop Yields

- The effects of climate change alone may reduce average yields of corn , soybeans, and wheat, both rainfed and irrigated, except in the northernmost latitudes where warmer conditions provide a longer frost-free growing season. Decreases in modeled yields result primarily from higher temperatures, which shorten a crop's life cycle.

- When the direct effects of CO_2 on crop photosynthesis and transpiration are approximated along with the effects of climate change, average rainfed and irrigated corn, soybean, and wheat yields could overcome the negative effects of climate change in some locations. If climate changes are severe, yields could still decline. The extent to which the beneficial effects of CO_2 will be seen under field conditions with changed climate is uncertain.

- Even if the patterns of climate variability are unchanged, yield stability may decrease, particularly under rainfed conditions. This may occur because there would be more days above temperature thresholds for particular crops in some locations. The exact magnitude will be sensitive to changes in climatic variability, particularly the frequency of droughts.

Economic Impacts

- Under three out of four scenarios, a small to moderate aggregate reduction in the nation's agricultural output was estimated. The estimated production levels appeared to be adequate to meet domestic consumption needs. If droughts occur more frequently under changing climate, effects on agriculture may be more severe.

- Assuming no change in export demand, reduced outputs would decrease exports, which could negatively affect global food supplies and the U.S. trade balance. This report did not reduce average yields of corn, soybeans, and analyze global changes in agriculture, which could have a major effect on demand for U.S. products.

- Under the most severe climate change scenarios, continued technological improvements, similar to those in recent years, would have to be sustained to offset losses. Increasing food demand from higher U.S. and world population would aggravate the economic losses due to climate change.

- The economic response of agriculture to changes in regional productivity may be able to shift crop production and associated infrastructure in a northward direction. This is because yields in northern areas generally increase relative to yields in southern areas. Although availability of agricultural soils was included in the economic analysis, neither the sustainability of crop production in the northern areas nor the introduction of new crops into the southern area was studied.

Irrigation Demand

- The demand for irrigated acreage is likely to increase in all regions. This is due to the reliability of irrigated yields relative to dryland yields and to higher commodity prices that make expansion of irrigated production more economically feasible. Actual increases in irrigated production more economically feasible. Actual increases in irrigated acreage would depend on the adequacy of water supply and on whether the cost of water to farmers increases

- Demand for more irrigation would increase stress on and competition for regional water supplies. If irrigation does increase, it would increase surface and groundwater pollution and other forms of environmental degradation.

Agricultural Pests

- Climate warming could change the ranges and populations of agricultural pests. Temperature increases may enhance the survival of insect pests in the winter, extend their northward ranges, increase pest species with more than one generation per year, and allow pest establishment earlier in the growing season. These effects could result in a substantial rise in pesticide use, with accompanying environmental hazards. Changes in pests will also depend on regional shifts in crop production.

Farm-Level Adjustments

- Farmers may adjust to climate change by using full-season and heat-resistant crop species or varieties, by altering planting dates, by planting two crops during one growing season, by increasing or altering their scheduling of irrigation, by using more pesticides, and by harvesting earlier. If climate change is not severe, these adjustments may mitigate losses in crop yields; more severe climate change is likely to make major adaptation necessary.

Livestock Effects

- Higher temperatures may increase disease and heat stress on livestock in some regions. Existing livestock diseases may shift north, while tropical diseases may extend their ranges into southern regions of the United States. Cold stress conditions may be reduced in the winter, but heat stress is likely to increase in the summer. Reproductive capabilities may also decrease.

Policy Implications

- Global climate change has important implications for all parts of the agricultural system. The agricultural research structure, which is dedicated to maintaining U.S. farm productivity, should expand climate change research in activities ranging from the field level to the national policy level.

- Current U.S. Department of Agriculture (USDA) research on heat- and drought - tolerant crops and practices and maintenance of crop germ plasm should be sustained and enhanced to limit vulnerability to future climate change.

- The USDA should evaluate current legislation in regard to its ability to allow adaptation to global warming. Flexibility in shifting crop types and farm practices will speed adjustment. Such adaptation strategies should consider the impacts on soil erosion and water quality.

- The USDA, the Department of Commerce, the U.S. Trade Representative, and the State Department should consider the implications of potential long-term changes in the level of

U.S. crop exports for the U.S. balance of trade and strategic interests.

- A national drought policy is strongly needed to coordinate federal response to the possibility of increased droughts due to climate change. Even without climate change, such a policy is necessary not only for the agricultural sector but also for other sectors.

SENSITIVITY OF AGRICULTURE TO CHANGES IN CLIMATE

Agriculture is a critical American industry, providing food for the nation's population and as much as $42.6 billion in exports for the nation's trade balance (Figure 6-1). Agriculture employs 21 million people -- more than any other industry, when taking into account workers on farms and in meat, poultry, dairy, baking, and food-processing activities (Council for Agricultural Science and Technology, 1988). The U.S. agricultural production system includes farm equipment manufacture, fertilizer and seed supplies, rural banking, and shipping. Total farm assets were $771 billion in 1985; food and fiber were 17.5% of the total gross national product in the same year. Wheat, corn, soybeans, cotton, fruits and vegetables, and livestock are among the most important U.S. agricultural commodities.

Worldwide, agricultural products must provide sustenance for the world's growing population, now estimated at about 5 billion and projected to rise to 8.2 billion by 2025 (Zachariah and Vu, 1988). Global production and consumption of grain have grown steadily since 1960, although regional food shortages continue to occur owing to climate variability and socioeconomic factors. Technological advances, such as improved hybrids and irrigation systems, have reduced the dependence of crop yields on local environmental conditions, but weather is still an important factor in agricultural productivity.

For example, failure of the monsoon season caused shortfalls in crop production in India, Bangladesh, and Pakistan in 1987. The 1980s have also seen the continued deterioration of food production in Africa, despite adequate world food supplied elsewhere, because of persistent drought, internal wars, poor distribution, weak infrastructure, and a deteriorating environment. Climate extremes have had large effects on U.S. agriculture. During the Dust Bowl years of the 1930s, U.S. wheat and corn yields dropped by up to 50%. Midsummer 1983 saw an

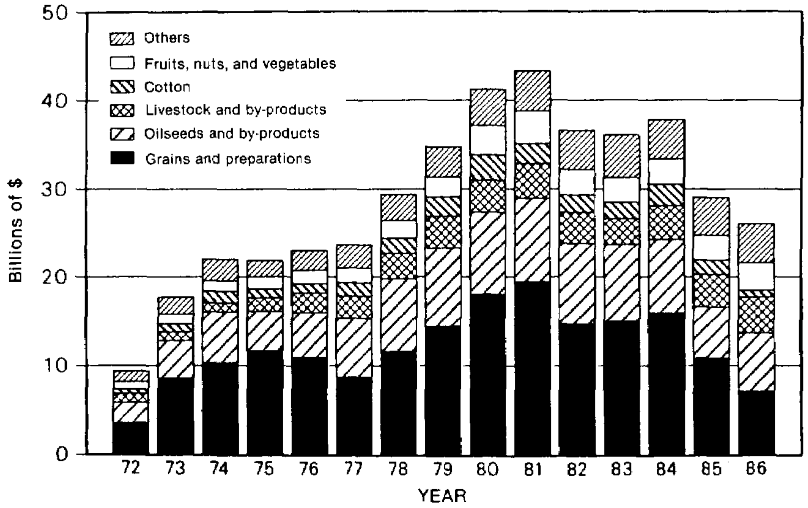


Figure 6-1. Value of U.S. agricultural exports by commodity, 1972-86 (not adjusted for inflation). Livestock excludes poultry and dairy products (The World Food Institute, 1987; U.S. Department of Agriculture, Economic Research Service, Foreign Agricultural Trade of the United States, Washington, DC, January-February 1987, and various other issues).

unpredicted drought in the U.S. Corn Belt and in the southeastern United States, causing U.S. corn yields to fall by about a third, from over 7,000 kilograms per hectare to about 5,000 kilograms per hectare (from about 110 to 80 bushels per acre).

The 1988 drought recently demonstrated the impact that climate variability can have on agricultural productivity. This drought decreased U.S. corn yields by almost 40%, and the cost of the 1988 Drought Relief Bill is estimated to be $3.9 billion (Schneider, 1988). The 1988 drought emphasizes anew the close link between agriculture and climate.

Light from the sun, frost-free growing seasons, and the hydrologic cycle largely govern the suitability of geographic areas for crop production and affect crop productivity. Livestock production is responsive to climate through differing levels of heat and cold stress and altered ranges of disease-carrying vectors such as mosquitoes and ticks.

Higher levels of CO_2 in the air would also affect crops. Increased CO_2 has enhanced crop photosynthesis and has improved crops' use of water in experimental settings. Because experimental research has rarely simultaneously investigated both the climatic and the direct effects of CO_2 on plants, it is difficult to assess the relative contributions of CO_2 and increased temperature to plant responses. This remains one of the most crucial questions in the analysis of impacts of climate change and increased CO_2 on agriculture.

The presence and abundance of pests affecting both crops and livestock are highly dependent on climate. The severity of the winter season, wind patterns, and moisture conditions determine in large part where pests will be prevalent. The geographical distribution of pests also depends on locations of crop types.

Much of U.S. agricultural production takes place under technologically advanced cropping systems that are primarily monocultural. Likewise, livestock production is highly specialized, both technically and geographically, and a high degree of integration exists between grain and livestock production. Any significant level of economic robustness associated with general, multipleenterprise farms has long since passed from the scene. The ability of our agricultural system to adapt to climate change may be more limited now in some ways than it was in the past.

Agriculture strongly affects the natural environment. It often increases soil erosion, intensifies demand for water, degrades water quality, reduces forested land, and destroys wildlife habitats. Many agricultural practices contribute to soil degradation, groundwater overdraft, loss of plant and aquatic communities, and generally reduced resilience in environmental and genetic resources. Therefore, climate-driven shifts in agricultural regions have implications for environmental quality.

Thus, climate plays a major role in determining crop and livestock productivity. Agricultural productivity determines profitability and decisionmaking at the farm level, which in turn define farming systems at the regional level and import-export supply and demand at the national and international levels. These complex interrelationships necessitate a broad consideration of the impacts of potential climate change on U.S. agriculture.

PREVIOUS STUDIES OF CLIMATE CHANGE AND AGRICULTURE

Relationships between climate and agriculture have been studied intensively for many years. However, relatively few studies have specifically addressed both the climatic and the direct effects that the growth in trace gases will have on agriculture. Even fewer studies have addressed these potential effects in an integrated approach that links both biophysical and economic spheres of analysis.

Most research attention in the United States, supported primarily by the U.S. Department of Energy, has focused on the direct effects of CO_2 on crops. These studies are reviewed by Acock and Allen (1985) and Cure (1985), who found an average increase in yields of about 30% and increases in water-use efficiency for crops growing in air with doubled CO_2 (660 ppm) and favorable, current climate conditions. Kimball (1985) and Decker et al. (1985) suggested that the potential effects of CO_2 and/or climate change on agricultural production systems may include shifts in production areas and changes in levels of livestock stresses, water availability, and pest control management.

Integrated approaches to the impacts of climate change on agriculture involving both biophysical and economic processes have been considered in studies by Callaway et al. (1982), the Carbon Dioxide Assessment Committee (1983), Warrick et al. (1986), and the Land Evaluation Group (1987). A benchmark international study on both the agronomic and economic effects of climate change on agriculture was conducted by the International Institute for Applied Systems Analysis (Parry et al., 1988). No study has as yet comprehensively examined the combined effects of climate change and the direct effects of CO_2 on U.S. agriculture.

CLIMATE CHANGE STUDIES IN THIS REPORT

Structure of and Rationale for the Studies

The regions studied for this report are important agricultural production areas (see Table 6-1). The Great Lakes and Southeastern States are major corn and soybean producers, and the Great Plains States grow mainly wheat and corn. California annually produces about 10% of U.S . cash farm receipts from cotton, grapes, tomatoes, lettuce, and many other crops.

The agricultural studies involve the following research topics (see Table 6-2): (1) crop growth and yield, (2) regional and national agricultural economics, (3) demand for water for irrigation, (4) water quality, (5) pest-plant interactions, (6) direct effects of CO_2 on crop growth and yield, (7) impacts of extreme events, (8) potential farm-level adjustments, (9) livestock diseases, and (10) agricultural policy.

Production of corn, wheat, and soybeans is critical to the economic well-being of the nation's farmers and the national trade balance. These crops make up about two-thirds of the total U.S. agricultural acreage, and their economic value is equal to that of all other crops combined. These three crops were selected for the modeling studies on the effects of climate change on yields.

The results from the regional studies of crop production (not including California), hydrological predictions from the climate models, and an agricultural economics model were linked in an integrated approach to enable investigators to translate the estimated yield changes from the crop modeling studies and predicted changes in water availability into economic consequences (see Figure 6-2). Such a coordinated analytical framework is necessary to account for the effects of market forces on the total agricultural sector, including livestock, and to evaluate the adequacy of the nation's resource base for agricultural production under climate change. Economic forces may lead farmers to grow more crops in areas with relatively high productivity and fewer crops in areas with relatively low productivity.

The studies of demand for irrigation water, water quality, and farm-level adjustment were also linked with the integrated modeling studies by common assumptions, sites, or outputs. Because California grows a large and diverse number of crop commodities, a simple approach was used to estimate crop yield changes for the California case study based on heat, sunlight, and photosynthetic response to CO_2. These yield changes were then used in a model of agricultural land and water use in California. Adjustment experiments were included in several studies to test possible adaptation mechanisms, such as changes in planting dates and crop varieties.

Table 6-1. Crop Production by Region.

EPA study areas	Corn	Wheat (thousands of bushels)	Soybeans	Harvested acres (thousands)
Southeast	311	272	306	29
Great Lakes	4,644	297	822	92
Great Plains	921	755	136	71
California	38	63	--	6
Total (48 states)	8,209	2,507	1,990	337

Table 6-2. Agriculture Projects for EPA Report to Congress on the Effects of Climate Change

Regional Studies

- Effects of Projected CO_2 Induced Climate Changes on Irrigation Water Requirements in the Great Plains States - Allen and Gichuki, Utah State University (Volume C)
- Climate Change Impacts upon Agriculture and Resources: A Case Study of California - Dudek, Environmental Defense Fund (Volume C)
- Farm-Level Adjustments by Illinois Corn Producers to Climate Change - Easterling, Illinois State Water Survey (Volume C)
- Impacts of Climate Change on the Fate of Agricultural Chemicals Across the USA Great Plains and Central Prairie - Johnson, Cooter, and Sladewski, Oklahoma Climatological Survey (Volume C)
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A.: A Simulation Study - Peart, Jones, Curry, Boote, and Allen, University of Florida (Volume C)
- Effects of Global Climate Chance on Agriculture: Great Lakes Reams - Ritchie, Baer, and Chou, Michigan State University (Volume C)
- Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study - Rosenzweig, Columbia University/NASA Goddard Institute for Space Studies (Volume C)

National Studies

- The Economic Effects of Climate Chanize on U.S. Agriculture: A Preliminary Assessment - Adams, Glyer, and McCarl, Oregon State University and Texas A&M University (Volume C)
- Analysis of Climate Variability in General Circulation Models - Mearns, Schneider, Thompson, and McDaniel, National Center for Atmospheric Research (Volume 1)
- Direct Effects of Increasing CO_2 on Plants and Their Interactions with Indirect (Climatic) Effects - Rose, Consultant (Volume C)
- Potential Effects of Climatic Change on Plant-Pest Interactions - Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center and Miami University (Volume C)
- Agricultural Policies for Climate Changes Induced by Greenhouse Gases - Schuh, University of Minnesota (Volume C)
- Changing Animal Disease Patterns Induced by the Greenhouse Effect - Stem, Mertz, Stryker, and Huppi, Tufts University (Volume C)
- Effect of Climatic Warming on Populations of the Horn Fly- Schmidtmann and Miller, USDA, Agricultural Research Service (Volume C)

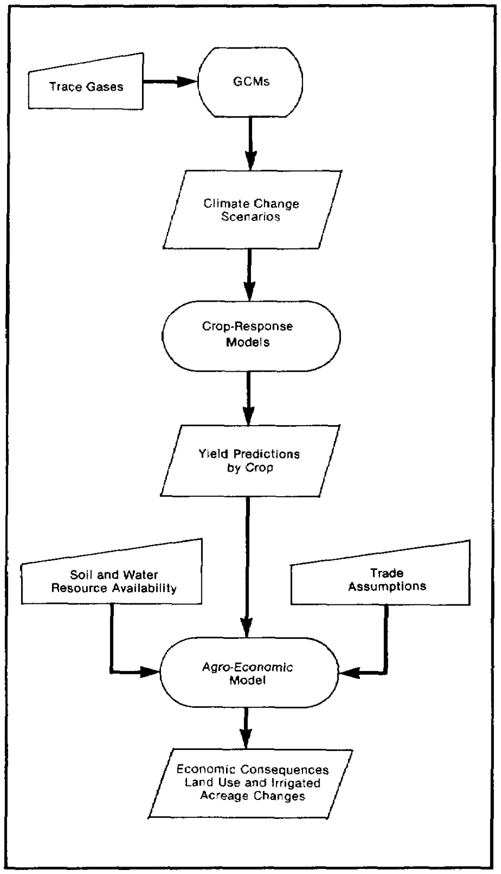


Figure 6-2. Flow chart of model interactions in EPA studies of the effects of global climate change on U.S. agriculture (Dudek, 1987).

The agricultural studies performed for this EPA report explore the sensitivities of the different parts of the agricultural system (shown in Table 62) to climate change scenarios. They are not meant to be predictions of what will happen; rather, they aim to define ranges and magnitudes of the potential responses as the system is currently understood. Regional results were extrapolated to other areas to give estimates of changes in national production.

Variability

All of the modeling studies used the doubled CO_2 climate change scenarios developed for the report (see Chapter 4: Methodology). These scenarios were developed from estimated changes in monthly mean climate variables from general circulation models (GCMs), without alterations in climate variability. For example, the number of days of precipitation remains the same in the baseline and climate change scenarios, and the amount of precipitation on each of those days is adjusted by the GCM ratio for climate change. Extreme events, such as maximum temperature, vary in the climate change scenarios according to the ratios, but the daily and interannual patterns of warm episodes are determined by the observed baseline climate.

The lack of changes in the daily and interannual patterns of extreme events may result in underestimation of impacts of climate change. This is because runs of extreme climate variables (for example, prolonged heat spells during grain filling and drought) can decrease crop productivity. For rainfed crops, yields may change considerably, depending on whether a change in precipitation is caused by more or fewer events or by higher or lower precipitation per event. The frequency, intensity, and/or duration of extreme climatic events can be much more consequential to crop yields than are simple changes in means.

Timing of Effects

The timing of climate change is uncertain - rates of future emissions of trace gases, as well as when the full magnitude of their effects will be realized, are unknown. CO_2 concentrations are estimated to be about 450 ppm in 2030 and 555 ppm in 2060 if current emission trends continue (Hansen et al., 1988). Other greenhouse gases besides CO_2 (e.g., methane (CH4), nitrous oxide (N_20), and chlorofluorocarbons (CFCs)) are also increasing. The effective doubling of CO_2 means that the combined radiative forcing of all greenhouse gases has the same radiative forcing as doubled CO_2 (usually defined as 600 ppm). The effective doubling of CO_2 concentrations will occur around the year 2030, if current emission trends continue. The climate change caused by an effective doubling of CO_2 may be delayed by 30 to 40 years or longer.

RESULTS OF AGRICULTURAL STUDIES

Regional Crop Modeling Studies

Design of the Studies

Widely validated crop growth models --

CERES-Wheat and CERES-Maize (Ritchie and Otter, 1985; Jones and Kiniry, 1986) and SOYGRO (Jones et al., 1988) -- were used to simulate wheat, corn, and soybean yields at selected geographically distributed locations within the Great Lakes, the Southeast, and the Great Plains. Representative agricultural soils were modeled at each site. California crop yield changes were predicted separately by using an agroclimatic index. (See the regional chapters, Chapters 14 through 17 of this report, for descriptions of individual studies.) Changes in temperature, precipitation, and solar radiation were included in the crop modeling studies. The crop models simulated both rainfed and irrigated production systems. The crop modeling approach allowed for analysis of latitudinal gradients in changes in crop yields and provided compatible results for each climate change scenario to be used as inputs in the agricultural economics study. (See Ritchie et al., Peart et al., and Rosenzweig, Volume C.)

The direct effects of CO_2 -- i.e., increased photosynthesis and improved water-use efficiency -- were also included with the climate change scenarios in some model runs to evaluate the combined effects. The direct effects were approximated by computing ratios of elevated CO_2 (660 ppm) to ambient CO_2 (330 ppm) values for daily photosynthesis (Table 6-3) and evapotranspiration rates (see Peart et al., Volume C, for detailed description of method).

Limitations

Uncertainties in the crop modeling studies reside in climate model predictions, locations of the climate stations (not always in production centers), crop growth models, and estimates of the direct effects of CO_2 . In particular, the climate change scenarios did not include changes in climate variability, even though changes in the frequencies of extreme events may considerably affect crop yields. Technology and cultivars were assumed not to change from present conditions.

Table 6-3. Increase in Daily Canopy Photosynthesis Rates Used in Crop Modeling Studies (%)

	Soybean	Wheat	Corn
Increase photosynthesis (%)	35	25	10

Source: Peart et al. (Volume C); Ritchie et al. (Volume C); Rosenzweig (Volume C).

The CERES and SOYGRO models describe relationships between plant processes and current climate. These relationships may or may not hold under differing climatic conditions, particularly the high temperatures estimated for the greenhouse warming. Lack of analysis of the nature and extent of agricultural soils at each modeling site adds uncertainty to the results.

The direct effects of CO_2 in the crop modeling results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, since the study assumed higher CO_2 levels (660 ppm) in 2060 than will occur if current emission trends continue (555 ppm), the simulated beneficial effects of CO_2 may be greater than what will actually occur.

Results

Under climate change scenarios alone, without the direct effects of CO_2, yields of corn, soybeans, and wheat were generally estimated to decrease in the Great Lakes, Southeast, and Great Plains regions, except in the northernmost latitudes, where warmer conditions provided a longer frost-free growing season. Figures 6-3 and 6-4 show change in modeled rainfed corn and soybean yields for the GISS and GFDL scenarios. The northern locations where yields increased included sites in Minnesota.

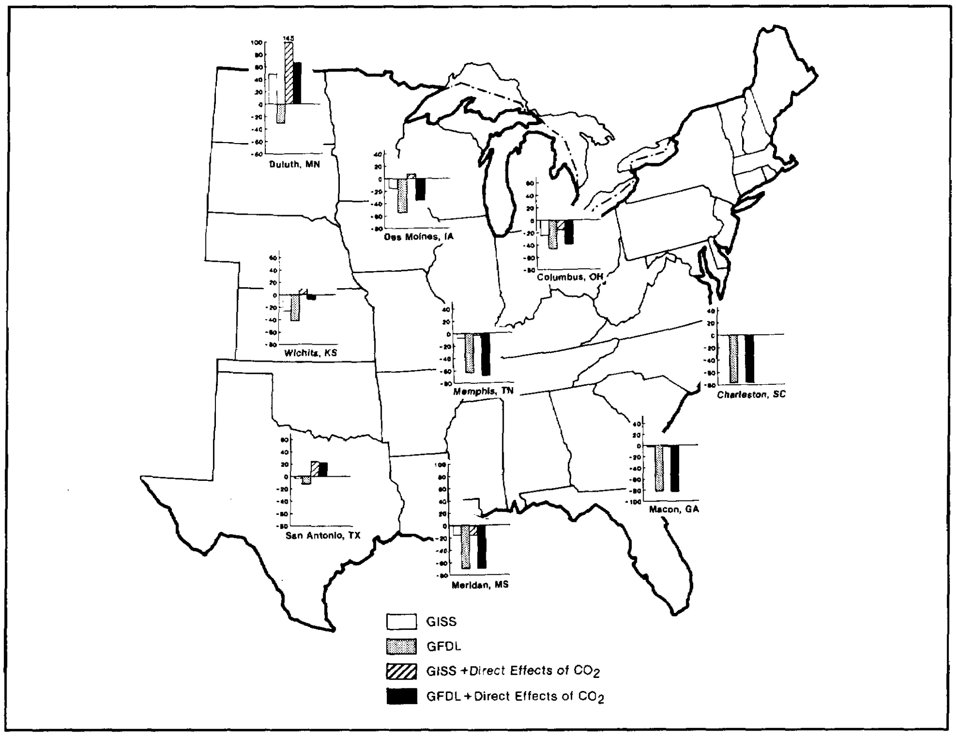


Figure 6-3. Percent change in rainfed corn yields simulated by the CERES-Maize model for baseline (195180) and GISS and GFDL climate change scenarios with and without the direct effects of CO_2 for selected locations (Peart et al., Volume C; Ritchie et al., Volume C; Rosenzweig, Volume C).

Decreases in modeled yields resulted primarily from higher temperatures, which would shorten the crop life cycle thus curtailing the production of usable biomass. In the Southeast, rainfall reductions were a major factor in the GFDL results. Modeled rainfed yields were estimated to decrease more than irrigated yields.

When increased photosynthesis and improved water-use efficiency were included in the crop models along with the climate change scenarios, yields increased over the baseline in some locations but not in others (see Figures 6-3 and 6-4). Particularly when combined with the hotter and drier GFDL climate change scenario in the Southeast, the direct effects of CO_2 would not fully compensate for changes in climate variables -- net yields were estimated to decrease significantly from the base case. Elsewhere, yields were generally estimated to increase, with relatively greater increases at the northern locations.

The crop models were also used to test several possible adaptations by farmers to the predicted climate changes. For example, a corn variety that is better adapted to longer growing seasons was tested in Indiana. Use of this later maturing variety would not compensate entirely for the yield decreases caused by the warmer climate change scenarios.

Implications

The potential for climate change-induced decreases in crop yields exists in many agricultural regions of the United States. In some northern areas, crop yields may increase. Farmers would need varieties of corn, soybeans, and wheat that are better acclimated to hotter and possibly drier conditions to substitute for present varieties.

If the major agricultural areas are to continue to provide a stable supply of food under the predicted changes in climate, supplemental irrigation may be required for many soils. Pressure for increased irrigation may grow in these regions. This could further tighten water supply problems in some areas and increase pollution from nonpoint sources (i.e., pollution that is not traceable to any one distinct source, such as

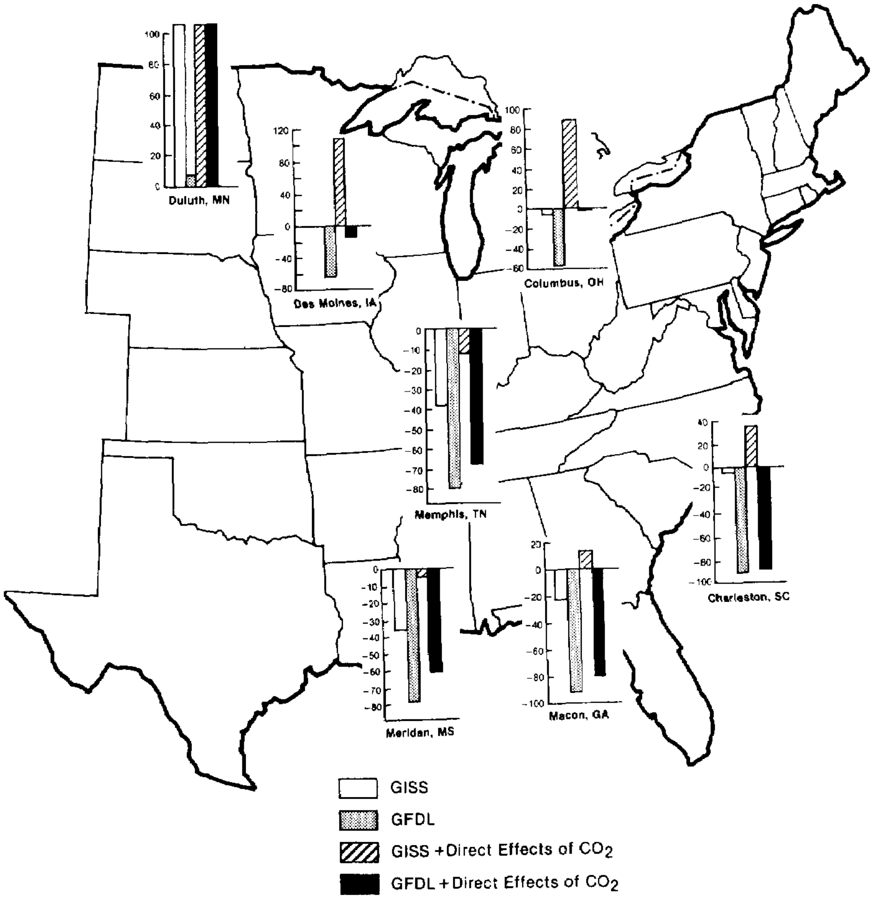


Figure 6-4. Percent change in rainfed soybean yields simulated by the SOYGRO model for baseline (1951-80) and GISS and GFDL climate change scenarios with and without the direct effects of CO_2 for selected locations (Peart et al., Volume C; Ritchie et al., Volume C).

agricultural chemicals from farmers' fields). Considerable uncertainty exists regarding the future availability of surface water and groundwater supplies with climate change, and concerning the competing demands for and costs of using or extracting the water (see Chapter 9: Water Resources).

Regional and National Economics Study

The estimated yield changes from the crop modeling studies (not including California) and projected changes in irrigation water demand and availability were introduced into an agricultural economic model to translate the physical effects of climate change into economic consequences. Adams et al. (see Volume C) estimated the regional and national economic implications of changes in yields of wheat, corn, soybeans, and other crops and in the demand for and availability of water associated with alternative global climate change scenarios.

Study Design

A spatial equilibrium agricultural model developed by Adams et al. (1984) was used to represent production and consumption of numerous agricultural commodities for the U.S. farm production regions as designated by the USDA (Figure 6-5). The model has been used to estimate agricultural losses due to increased ultraviolet-B (UV-B) radiation caused by stratospheric ozone depletion (Adams et al., 1984). It consists of farm-level models for production regions, integrated with a national-level model of the agricultural sector. Acreage available for production is based on current definition of agricultural land classes. Both irrigated and nonirrigated crop production and water supply relationships are included for most regions. The model simulates a long-run, perfectly competitive equilibrium and was developed using 1980-83 economic and environmental parameters.

A set of model runs was conducted, using the GISS and GFDL climate change scenarios, with and without the direct effects on crop yields. Potential changes in technology and in future U.S. and world food demand due to population growth were also introduced into the climate change analysis.

Limitations

The economic approach used in this study has several limitations. The economic model is static in the sense that it simulates an equilibrium response to climate change, rather than a path of future changes. Substitution of crop varieties, new crops, and adjustments in farm management techniques were not included; thus, the negative effects of climate change were possibly overestimated. Since CO_2 levels were assumed to be high in the crop modeling study, estimates of the beneficial direct effects of CO_2 on crop yields may have biased the economic results in the positive direction in some scenarios.

Furthermore, changes in yields used as inputs to the economic model were modeled for only wheat, corn, and soybeans for a limited number of sites and regions. The regional crop yield analyses cover 72% of current U.S. corn production, 33% of wheat production, and 57% of the soybean output. National estimates were extrapolated from these for all other crop commodities in the model. Changes in risk, where risk is defined as increases in variance of crop yields, were not explicitly included in the economic analysis. The accuracy of the estimates of changes in water supply and crop water requirements derived from the GCMs cannot be ascertained. Potential increases in the demand for water by nonagricultural users, which would reduce water available for irrigation, were not included. All of these assumptions introduce uncertainties into the results.

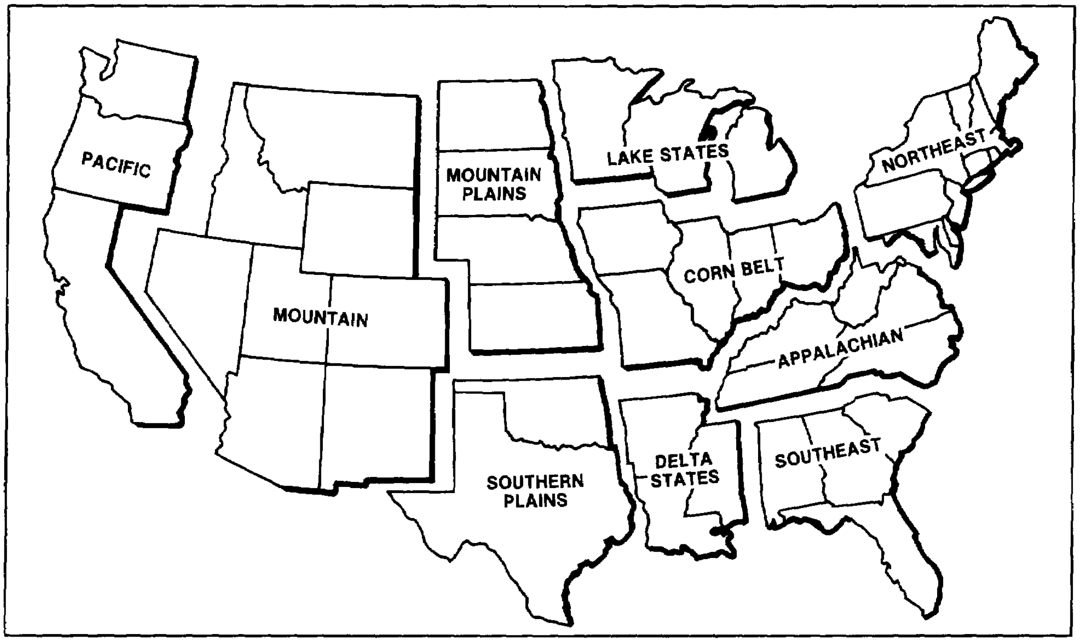


Figure 6-5. Farm production regions in the United States (USDA, 1976).

Table 6.4. Aggregate Economic Effects of GISS and GFDL Doubled CO_2 Climate Change on U.S. Agriculture with and without the Direct Effects of CO_2 on Crop Yields.

	Economic effects (billions of 1982 dollars)		
Run	Consumer	Producer	Total
GISS Analysis 4a: without CO_2	-7.3	1.5	-5.9
GISS Analysis 4: with CO_2	9.4	1.3	10.6
GFDL analysis 4: without CO_2	-37.5	3.9	-33.6
GFDL Analysis 4: with CO_2	-10.3	0.6	-9.7

[a] Analysis 4 includes the crop yield and irrigation water supply demand consequences of climate change throughout the United States
Source: Adams et al. (Volume C).

Potential changes in international agricultural supply, demand, and prices due to climate change are not explicitly included in the model. Such changes could have major impacts on U.S. agriculture. For example, warming may enhance the agricultural capabilities of high-latitude countries such as Canada and the U.S.S.R. While the net effect of climate change on the rest of the world is uncertain, global changes could overwhelm U.S. national impacts. A net negative effect on agriculture abroad would improve the position of U.S. agricultural producers through enhanced exports, but could increase the negative impacts on U.S. consumers through increases in global commodity prices.

Results

It is important to note that the results of the economic study are not predictions. Rather, they are initial estimates of how the current agricultural system would respond to the projected climate change scenarios.

The economic model showed a small to moderate aggregate loss in economic welfare associated with the estimated crop yield and hydrologic changes derived from the climate change scenarios (see Table 6-4). For the moderate GISS climate change scenario, net losses were small; for the more extreme GFDL scenario, they were greater. The magnitudes of these changes, which are annual, may be compared with the estimated $2.5 billion (in 1982 dollars) in agricultural losses due to increased UV-B radiation caused by stratospheric ozone depletion of 15% (Adams et al., 1984). In general, consumers lose and producers gain because of the increased prices of agricultural commodities and inelastic demand (i.e., insensitivity to price changes) for agricultural crops.

Higher CO_2 levels could reduce negative economic impacts (Table 6-4). Under the less severe GISS climate scenario, the CO_2 direct effects were estimated to sufficiently counter the climatic effects in most regions, so that both producers and consumers gain. With the more severe GFDL climate change scenario combined with the direct effects of CO_2, lower yields led to higher prices, but not by as muA as occurred with the climate change scenarios alone. However, significant changes in regional agricultural land use occurred even when the beneficial direct effects of CO_2 were taken into account.

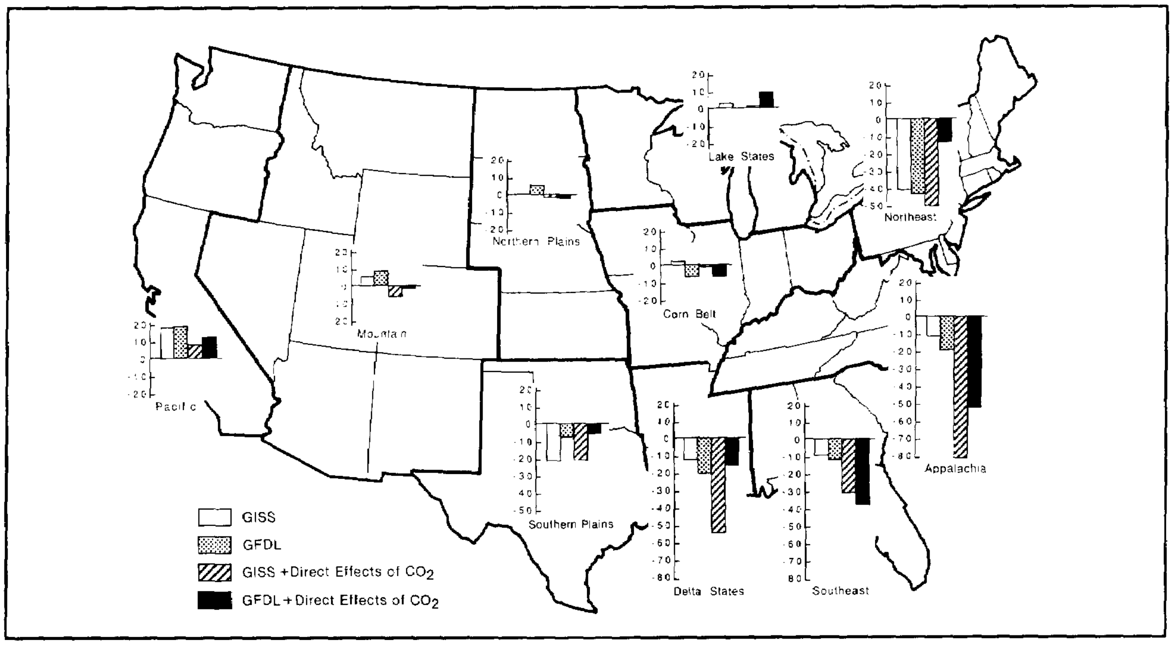


Figure 6.6. Percent change in regional agricultural acreage simulated by an economic model of the U.S. agricultural sector for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields (Adams et al., Volume C).

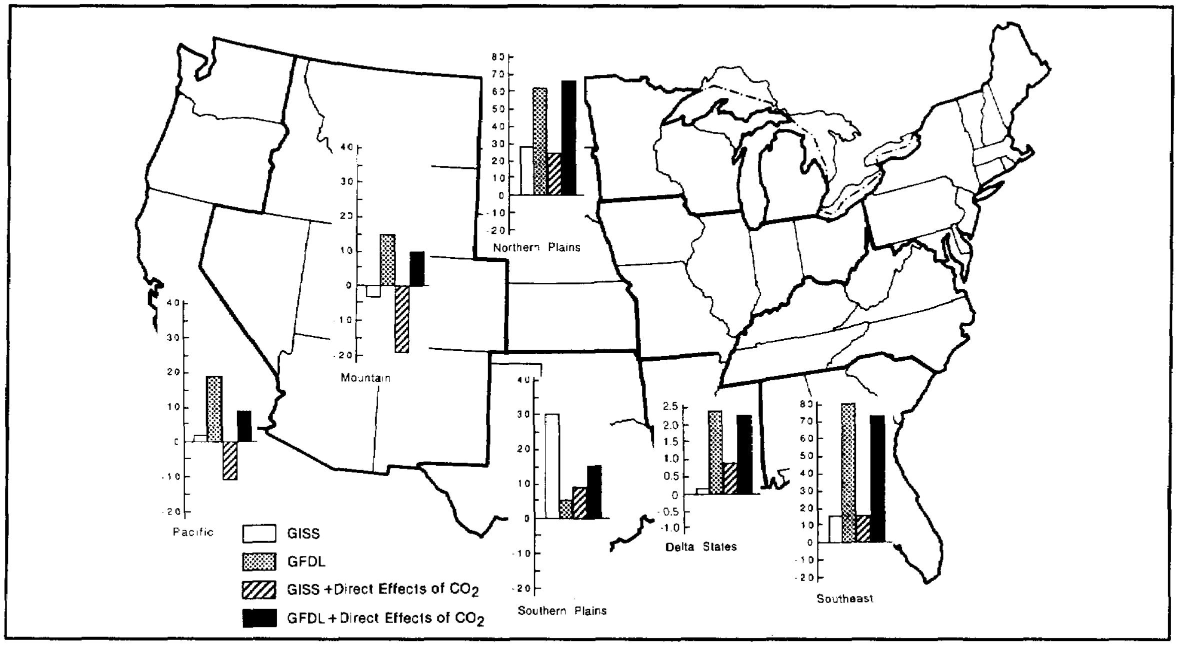


Figure 6-7. Change (100,000s of acres) in regional irrigation acreage simulated by an economic model of the U.S. agriculture sector for the GISS ans GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields. Changes are not shown in the Great Lakes, Corn Belt, Appalachia, and Northeast because currently irrigated acreage is small (2% of the total U.S. irrigated acreage) in these regions (Adams et al., Volume C).

Production of most crops was reduced because of yield declines and limited availability of land and resources. With climate change alone, corn production decreased 12 and 47% in the GISS and GFDL scenarios, respectively, while soybean production was estimated to be reduced by 12 and 53% for the same scenarios. In all scenarios, land under production in Appalachia, the Southeast, the Mississippi Delta, and the Southern Plains could decrease on average by 11 to 37%, while in the Lake States, the Northern Plains, and the Pacific it could increase by small amounts (see Figure 6-6). While availability of agricultural soils was included in the economic analysis, the sustainability of crop production in northern areas was not studied.

Irrigated acreage was estimated to increase in all areas, primarily because irrigation becomes economically feasible as agricultural prices rise (see Figure 6-7). These changes reflect both increased demand by farmers for irrigation water and changes in water availability as estimated by the GCM scenarios, but do not take into account changes in competition with industrial or municipal users.

Technological changes, such as higher yielding crop varieties, chemicals, fertilizers, and mechanical power, have historically enabled agriculture to increase production with the same amount of, or less, land, labor, and other resources. When the effect of future technological change (based on yield increases from 1955 to 1987) was modeled along with the less severe GISS climate change (without the direct effects of CO_2), most of the adverse climate effects were estimated to be offset. Under the severe GFDL climate change scenario, continued and substantial improvements in yields would be required to overcome the climate change effects. Stated another way, the adverse effects of climate change could negate most of the higher output attributable to improved technology over the next 50 years. It is important to note, however, that the rate of future technological advances is very difficult to predict. Increasing food demand from higher U.S. and world population aggravated the estimated economic losses from the climate change scenarios.

Implications

Food Supply and Exports

The economic analysis implies that although climate change could reduce the productive capacity of U.S. agriculture, major disruption in the supply of basic commodities for American consumers would not occur. Domestic consumers would face slightly to moderately higher prices under some analyses, but supplies could be adequate to meet current and projected domestic demand. However, if droughts occur more frequently under changed climate, effects on agriculture may be more severe.

Exported commodities in some scenarios decline by up to 70%, assuming the demand for exports remains constant. Thus, climate change could affect the United States in its role as a reliable supplier of agricultural export commodities. It is likely that supply of and demand for agricultural commodities could shift among international regions, and responses of U.S. agriculture will take place in this global context. There is a great need to determine the nature of these changes in global agriculture by analyzing the potential impacts of climate change on both major world agricultural production regions and potentially vulnerable food deficit regions.

Regional Economics and Land Use

Regional shifts in U.S. agricultural production patterns (not only grain crops but also vegetables and fruits) are highly likely, as all climate change scenarios tested show that the southern areas of the United States become less productive relative to the northern areas. This is primarily because the high temperatures estimated for climate change would stress crop production more in southern areas than in northern areas where crops are currently limited by lower temperatures and shorter growing seasons. However, increased agricultural production may be difficult to sustain in the North, because some soils may be less fertile and may have lower water-holding capacity. Crops grown in soils with lower water-holding capacity require more evenly distributed rainfall to produce comparable yields.

Regional changes in agriculture would have important implications for rural communities. As production areas shift, climate change effects would reverberate through these communities and are likely to result in structural changes in local economies, such as relocation of markets and transportation networks. At its most extreme, climate change could cause dislocation of rural communities through farm abandonment.

Environmental Concerns

Regional agricultural adjustments could place environmental resources at risk. Where agricultural acreage would increase, demands for natural resources, such as soil and water, might intensify current pressures on environmental elements, such as rivers, lakes, aquifers, wetlands, and wildlife habitats. Northern States, such as Minnesota and North Dakota, could become more productive for annual crops like corn and soybeans because of warmer temperatures and a longer frost-free growing season. Given the presence of forests and wetlands in these regions, increased agricultural production in the area might threaten natural ecosystems, including wildlife habitats such as prairie potholes for ducks and flyways for bird migrations.

In addition, many of the glacial till soils in the northern latitudes are not as productive as Corn Belt soils. Thus, large increases in production of crops would most likely require greater applications of chemical fertilizers. The use of these fertilizers in humid regions on glacial till and sandy soils is now creating an environmental hazard to the underlying groundwater, receiving waters, and aquatic habitats in many areas. With climate change, water and fertilizer use would have to be carefully managed to minimize still more leaching of water-soluble nutrients such as nitrogen and potash.

Demand for Water for Irrigation

Water is the single most critical factor in determining the development, survival, and productivity of crops. The amount of water that crops use and thus the demand for irritation water are governed largely by the evaporation process. Higher air temperatures due to increasing trace gases in the atmosphere could heighten evaporative demands. Increased irrigation to satisfy these higher demands could accelerate depletion of groundwater and surface water resources. Also, the rate of evaporation might outstrip precipitation, thus decreasing crop yields.

Studies reported in the California and the Great Plains case studies (see Chapters 14 and 15) explicitly examined the potential changes in demand for water for irrigation. The studies did not consider changes in competing demands for water such as industrial and residential use, which also may change in a warmer climate. The California study, however, considered changes in supply due to earlier snowmelt and sea level rise. In these regions, water is a critical resource for agriculture; California and the parts of the Great Plains fed by the Ogallala Aquifer, in particular, depend very heavily on irrigation for crop production.

Irrigation Requirements in the Great Plains

Allen and Gichuki (see Volume C) computed irrigation water requirements for sites in the Great Plains for the baseline climate and the GISS and GFDL climate change scenarios. The direct effect of CO_2 on water use was also included. (For study design and limitations, see Chapter 17: Great Plains.) Major changes in irrigation water requirements were estimated for all locations in the Great Plains and for all crops (see Figure 6-8). The most significant would be the persistent increases in seasonal net irrigation water requirements for alfalfa, which would be driven by the climate changes in temperature, wind, humidity, and solar radiation, and by the lengthening of the growing season. Decreases in irrigation requirements were estimated for winter wheat in most regions. These decreases would be the result of earlier planting dates and shorter crop life cycle due to high temperatures. When crop varieties appropriate to the longer growing season were modeled, irrigation water requirements for winter wheat were estimated to increase. Simulated irrigation water requirements during peak periods increased in almost all areas (see Figure 6-9).

While farmers in the Great Plains would probably shift to longer season crops, climate change conditions (warmer temperatures and drying in some areas) during the later summer months could increase irrigation requirements and elevate leaf temperatures to a point that exceeds optimum temperatures required for high productivity. This might make it uneconomical to take full advantage of the longer growing season, especially if the higher CO_2 levels increase photosynthesis and offset the effects of a shorter season to some degree.

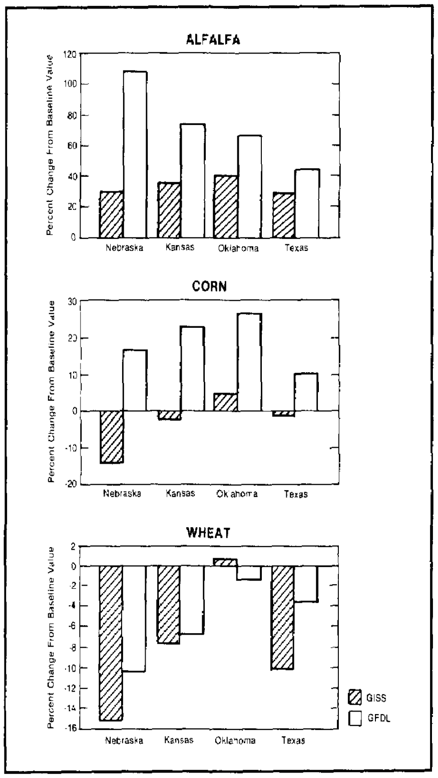


Figure 6-8. Percent change in net seasonal irrigation requirements for GISS and GFDL climate change scenarios with direct effect of CO_2 on crop water use included (Allen and Gichuki, Volume C).

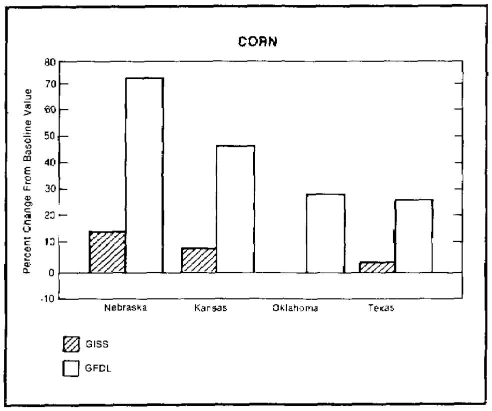


Figure 6-9. Percent change in peak irrigation requirements of corn for GISS and GFDL climate change scenarios with direct effect of CO_2 on crop water use included (Allen and Gichuki, Volume C).

Water Resources for Agriculture in California

In the California regional case study, Dudek (see Volume C) characterized the potential shifts in demand for water for agricultural production that would accompany shifts in cropping patterns driven by changing climate. Changes in competing demands for water from industrial or municipal users were not considered. (For description of study design and limitations, see Chapter 14: California.) When climate change was considered alone, groundwater extraction and surface water use were estimated to decline in California as a result of changes in both supply of (derived from GCM climate change scenarios) and agricultural demand for water. When the direct effects of CO_2. on crop yields were included, groundwater extraction would increase because of improved yields of all crops except corn and because of enhanced economic welfare. Institutional responses to changes in surface and groundwater use could include water transfers, which could improve irrigation efficiency. When water markets were included in the simulations, economic welfare was improved by 6 to 15% over the base, while crop acreage increased and groundwater extraction decreased.

Implications for Demand for Irrigation Water

Expanded use of irrigation is implied from the regional crop modeling studies for the Great Lakes, the Southeast, and the Great Plains (see Chapters 15, 16, and 17, respectively). Increases in irrigated acreage are also estimated for most regions when the economics of crop production are factored in (see Adams et al., Volume C). When these results are considered along with the irrigation studies, it appears that climate change is likely to increase the demand for water from the agricultural sector in many regions.

In the Great Plains, heightened evaporative demand and variability of rainfall may increase the need for irrigation in dryland farming regions. The simulated changes in irrigation water requirements are varied, and specific crops and locations probably would be affected differently. Higher peak irrigation water requirements for some crops may require larger capacity irrigation systems and may enlarge energy demands.

Intensified extraction of water poses serious environmental and economic problems, especially in areas where groundwater is being overdrawn. Streamflows also may slacken if more surface water is used for irrigation, thereby aggravating water quality problems. This in turn would harm fish, wildlife, and recreational activities.

Regional changes in cropping locations and patterns of water use also could exacerbate agricultural, nonpoint source pollution, and could further deplete groundwater resources. Institutional responses, such as markets for water transfers, could help improve irrigation water management and alleviate some of these negative effects.

The economic and social costs of shifting the location of irrigated agriculture could be considerable. The construction of irrigation systems consisting of reservoirs, wells, ditches, pipes, pumps, and sprinklers currently requires about $1,500 to $5,000 per hectare in capital investment (Postel, 1986).

Direct Effects of CO_2 on Crops

Global increases in CO_2 are likely to influence crop metabolism, growth, and development directly through physiological processes and indirectly through climate. Rose (see Volume C) reviewed recent experimental work performed on the direct effects of CO_2 on crops, with emphasis on wheat, corn, soybeans, and cotton.

Elevated concentrations of CO_2 directly affect plant processes such as photosynthesis and transpiration. Higher CO_2 concentrations are also expected to influence these processes indirectly through predicted increases in temperature and other changes in climate variables such as precipitation. Because experimental research has rarely simultaneously studied both the direct and indirect effects of plant responses, it is difficult to assess the relative contributions of elevated CO_2 and climate changes to predictions of crop responses.

Research on the physiological effects has focused primarily on responses of rates of photosynthesis and transpiration to increasing concentrations of atmospheric CO_2. Photosynthesis rates have increased in these crops in relatively ideal experimental environments. At moderate temperatures, most crops will probably show increases in size and possibly yield as CO_2 concentrations rise. However, plants also have internal regulation mechanisms that may lessen these effects under field conditions.

Transpiration rates per unit leaf area decrease, while total transpiration from the entire plant sometimes increases because of greater leaf area. Drought-stressed plants exposed to high partial pressures of CO_2 should be better able to cope with water deficits. Leaf temperatures in all species are expected to rise even more than air temperatures; this may inhibit plant processes that are sensitive to high temperature.

Few studies have examined the interactive effects of CO_2, water, nutrients, light, temperature, pollutants, and sensitivity to daylength on photosynthesis and transpiration. Even fewer studies have examined the effects of these interactions on the growth and development of the whole plant. Therefore, considerable uncertainty exists concerning the extent to which the beneficial effects of increasing CO_2 will be seen in crops growing in the field under normal farming conditions with climate change.

Climate Impacts on Pest-Plant Interactions

Compared with the existing information on the potential effects of climate change on crop production, relatively little effort has been directed toward assessing the influence of climate change on plant-pest interactions. Atmospheric increases in temperature and CO_2, and changes in moisture regimes, all can directly or indirectly affect interactions between pests and crops. Changes in pests will also depend on regional shifts in crop production. Although crop pests may be defined as weeds, insects, or disease pathogens, the EPA work on this subject focused on insects.

Study Design and Results

Stinner et al. (see Volume C) conducted a literature survey and modeling experiments on the major mechanisms through which climate change may affect pest-plant interactions. This study emphasized the major insect pest and pathogen species of corn and soybeans. The survey indicates that temperature and precipitation patterns are the key variables that affect crop-pest interactions. The temperature increases associated with the climate change scenarios would bring about the following trends: (1) increased survival for migratory and nonmigratory insect pest species in the winter; (2) northern range extensions of current pests in the higher latitudes and migration of southern species into the northern Grain Belt regions; (3) an increase in pest species with more than one generation per year in the northern Grain Belt; (4) earlier establishment of pest populations in the growing season; and (5) increased abundance of pests during more susceptible crop growth stages.

The potential changes in the overwintering ranges of four major pests were mapped for the GISS and GFDL climate change scenarios and were compared to present ranges. The overwintering capability of the four major pests may extend northward with both climate change scenarios.

For example, the potato leafhopper, a serious pest on soybeans and other crops, at present overwinters only in a narrow band along the coast of the Gulf of Mexico (Figure 6-10). Warmer winter temperatures in the GFDL and GISS scenarios could cause a doubling or tripling of the overwintering range in the United States, respectively. This would increase the invasion populations in the northern states by similar factors. The invasions also would be earlier in the growing season, assuming planting dates do not change. Both features are likely to lead to greater insect density and damage. This pattern is repeated with the other three pests studied and indicates that these pests, and possibly others, may move northward and invade cropping systems earlier in the growing season under climate change conditions.

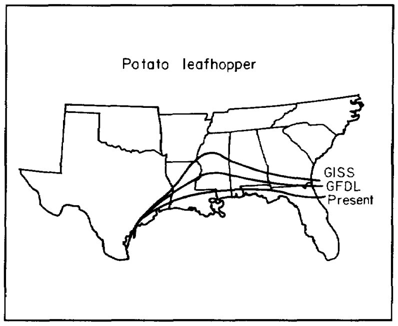


Figure 6-10. Present and potential (GISS and GFDL climate change scenarios) overwintering range of the potato leafhopper, Empoasca fabae, a major pest of soybeans (Stinner et al., Volume C).

The Soybean Integrated Crop Management (SICM) model (Jones et al., 1986) was run with the GISS and GFDL climate change scenarios to estimate changes in damages caused by corn earworm. Modeling results show that earworm damage to soybeans would increase in severity in the Grain Belt under a warmer climate. Such damage could cause grain farmers in the Midwest to suffer significant economic losses. These results were particularly marked with the warmer and drier GFDL scenario.

Limitations

Lack of knowledge about the physiological effects of CO_2 on crop plants and lack of experimental evidence of direct CO_2 effects on insect-plant interactions make the study of pestplant interactions particularly difficult. Only one cultivar was used in the modeling study under both the baseline and the climate change scenarios, and planting dates remained the same. In reality, farmers would probably switch to a more climatically adapted cultivar as climate changed, and they would advance planting dates in response to longer growing seasons.

Implications

Increased pest-related crop damage could intensify pesticide use. The economic and environmental ramifications of such an increase could be substantial, not only in current farming regions but also in new areas if agriculture shifts to the more northern regions such as the northern Plains, the Great Lakes States, and the Pacific Northwest (see Figure 6-6).

Increased use of pesticides would create additional threats to the integrity of ecosystems through soil and water contamination and could increase risks to public health. If agricultural production is not to rely increasingly on chemicals that are potentially harmful to the environment, an increased need will exist for alternative pest management strategies such as biological control, genetic resistance, and innovative cropping systems.

Effects of Climate Change on Water Quality

Agricultural pesticides are ranked as a high-priority pollution problem in many rural regions.

Potentially toxic agricultural chemicals can be transported away from fields via runoff of surface soils and via downward leaching and percolation through the soil. An understanding of these processes is needed to evaluate potential threats to drinking water quality caused by climate change.

Study Design

Johnson et al. (see Volume C) modeled the partitioning of agricultural pesticides among uptake, degradation, surface runoff, and soil leaching for wheat, corn, and cotton production regions in the Great Plains and the Corn Belt. (For details of the study, see Chapter 17: Great Plains.) They used the **Pesticide Root Zone Model (PRZM)** (Carsel et al., 1984), which simulates the vertical movement of pesticides in the soil. The model consists of hydrological and chemical transport components that simulate runoff, erosion, plant uptake, leaching, decay, foliar washoff, and volatilization of a pesticide. The interactions among soil, tillage, management systems; pesticide transport, and climate change were studied.

Limitations

The frequency and duration of precipitation remain the same in the climate change scenarios, even though these storm characteristics are critical factors in determining the transport of agricultural chemicals and may change. The scenarios assume that the number of days with rainfall does not change, but the intensity of rainfall increases or decreases. Runoff and leaching estimates would most likely be different if the number of days of rainfall changed and daily rainfall amounts were held constant.

The PRZM is a one-dimensional, point model that does not simulate the transport of water below the root zone. Thus, results on a regional basis must be extrapolated with care. The direct effects of CO_2 on crop growth, which may increase the size of the plants and the extent to which crops cover the soil, are not included.

Table 6-5. Summary of GISS and GFDL GCM Model Consensus of PRZM Pesticide Transport by Copping Region and Pesticide[a]

Crop and pesticide type	Surface pesticide runoff losses	Surface pesticide erosion losses	Pesticide leaching
Spring wheat			
Highly soluble/short-lived	+	+	-
Highly soluble/long-lived		+	-
Slightly soluble/long-lived			-
Winter wheat			
Highly soluble/short-lived		+	+
Highly soluble/long-lived	+		-
Slightly soluble/long-lived			-
Cotton			
Highly soluble/short-lived	+		+
Highly soluble/long-lived	+	+	-
Slightly soluble/long-lived	+	+	-
Corn			
Highly soluble/short-lived	-	-	
Highly soluble/long-lived		-	-
Slightly soluble/long-lived	-	-	-

[a] + indicates that median values increase under climate change; - indicated that median values decrease under climate change; blank indicates no consensus among median values.

[b] Example: median values of all tillage, soil, weather scenarios for highly soluble/short-lived pesticides in the spring wheat crop area.

Source: Johnson et al. (Volume C).

Results

Regional changes in chemical loadings of water and sediment are likely due to climate change but probably will not be uniform. There appears to be some consensus between the GCM scenarios concerning the estimated regional changes (Table 6-5). Modeled pesticides in runoff increase in the cotton production area, and pesticides carried by sediments decrease in the spring wheat and corn regions. Leaching of pesticides tends to be less everywhere owing to changes in seasonal precipitation and increased evaporation.

Implications

When the changes in water quality from the predicted climate change scenarios are considered in conjunction with the estimated increases in pests and implied higher applications of pesticides described in the study on pest-plant interactions, the potential for changes in the nation's water quality becomes apparent. Any deterioration in water quality could adversely affect public drinking water supplies and human health.

Climate Variability

The impacts of climate change result not only from a slow change in the mean of a climate variable but often from shifts in the frequency of extreme events. Droughts, freezes, and prolonged periods of hot weather have strong effects on agricultural production. Although the agricultural modeling studies did not include the effects of potential changes in climate variability, a review of literature on agriculture and extreme events that focuses on the nature and magnitudes of significant impacts is included in Chapter 3: Climate Variability.

Corn, soybeans, wheat, and sorghum are sensitive to high maximum temperatures during blooming. Lower yields of corn, wheat, and soybeans have been correlated with high temperatures. The damaging effect of runs of hot days on corn yields was particularly evident in the U.S. Corn Belt in 1983.

Although the problems associated with low temperatures may diminish with climate change, risks of frost damage to crops may change in the growing areas of certain crops. Citrus trees are very vulnerable to low minimum temperatures. Winter wheat is often damaged by low temperatures known as winter kill, especially in the absence of snow. Even with warmer winters and fewer frosts, more damage may occur at less extreme temperatures. For example, the effect of freezing temperatures is exacerbated if crops have not yet been hardened by cold temperatures or if the crops are no longer dormant and a cold snap occurs.

Drought is a major cause of year-to-year variability in crop production. In the Dust Bowl years of the 1930s, yields of wheat and corn in the Great Plains dropped to as much as 50% below normal. In 1988, agricultural disaster in areas of the northern Great Plains demonstrated a high vulnerability to drought, and nationwide corn yields decreased by nearly 40%. Reduction in vegetative cover associated with drought also brings about severe wind erosion of soils, which will affect future crop productivity. Low yields of forage crops during droughts result in food shortages for livestock and premature selling of livestock. If frequency of drought increases with climate change, impacts on agriculture can be severe.

Farm-Level Management and Adjustments to Climate Change

Adjustments to existing production practices would be the first course of action in the face of climate change. The net effect of climate change with adjustment by farmers may be significantly different from the estimated effects of climate change alone.

Study Design

Several studies addressed possible adjustments that could modify the effects of climate change. These adjustments include changes in planting and harvesting dates, tillage practices, crop varieties, application of agricultural chemicals, irrigation technology, and institutional responses for water resource management.

Results

Ritchie et al. demonstrated that the yield reduction in corn in the Great Lakes could be partly overcome with selection of new varieties that have a longer growing season (see Chapter 15: Great Lakes). Rosenzweig (see Chapter 17: Great Plains) showed that adjusting the planting date of winter wheat to later in the fall would not ameliorate the effects of climate change, but that changing to varieties more suited to the predicted climate could overcome yield decreases at some locations.

Dudek's California study found that flexible institutional responses to climate change would help to compensate partly for negative climate change effects (see Chapter 14: California). By allowing movement of water around the state by transferral of water rights, California's water resource managers could alleviate some groundwater extraction and compensate for surface water reductions.

Easterling (see Chapter 15: Great Lakes) found that potential farmer adjustments to climate change include changes in tillage practices, increased application of fertilizers, selection of more full-season and heat-resistant varieties, changes in planting densities, higher use of pesticides, earlier harvest, and reduced artificial drying. Different adjustments could occur at different times in the cropping season. With the hotter and drier GFDL scenario, farmers may have to adopt production practices different from those in use today. Climate changes that leave soils drier during summer than they are at present will most likely lead to an increased use of irrigation in the Corn Belt. This increased irrigation is also supported by the projected price increases for all crops grown in Illinois.

Implications

Although detrimental climate change effects on agriculture may be partly offset naturally by increased photosynthesis and water-use efficiency caused by higher levels of atmospheric carbon dioxide, farmers themselves would use a variety of adjustments to adapt to climate change. Market forces also would aid adaptation to climate change because they help to allocate resources efficiently. Each crop and region would respond differently to climate change, and adjustment strategies would need to be tailored to each situation.

Costs of adjustments are likely to vary considerably from region to region. Costs would be relatively small in regions where farmers can switch from one variety to another or from one grain crop to another, thus enabling continued use of existing farm machinery and marketing outlets. However, at locations near the present limit of major agricultural regions (e.g., the boundary between wheat farming and ranching), relatively small changes in climate may require a substantial switch in type of farming. This may require substantial costs in new equipment and other changes in agricultural infrastructure. Severe climate change may necessitate farm abandonment in some regions.

Improvements in agricultural technology also may be expected to ease adjustment through development of appropriate farming practices, crop varieties, and livestock species. Adjustment and adaptation to climate change should be included in agricultural research programs to enable this process to occur.

Livestock

Animal products are a critical source of protein, energy, vitamins, and minerals. U.S. livestock production, mainly from cattle, swine, sheep, and poultry, was estimated to be worth over $31 billion in 1986 (USDA, 1987).

Climate is known to significantly affect many aspects of animal health and production. The direct effects of climate warming on animal health include differences in incidence of heat and cold stress, changes in weight gain, and decline in reproductive capabilities. Indirect effects may involve trends in the availability and prices of animal feeds and the expanded geographic distribution and activity of disease-carrying vectors.

Higher winter temperatures may lower the incidence of respiratory diseases in livestock (Webster, 1981). Conversely, warmer summers may necessitate more hours of indoor cooling during which pathogens are confined to housing structures. Climate warming may significantly increase the costs of air-conditioning in poultry housing. Changes in reproductive capabilities such as decreased ovulation rates, shortened intensity and duration of estrus, decreased fertility of males, and increased embryonic mortality also have been shown to occur with high temperatures (Ames, 1981).

Climate change may also affect the

survivability, activity, and geographic distribution of vectors responsible for the transmission of infectious diseases in livestock. The activity and reproduction of disease-carrying vectors infecting livestock, humans, and crops are driven primarily by temperature, humidity, and precipitation. These impacts are likely to be similar to those on mortality and morbidity of disease in humans (see Chapter 12: Human Health), and they also are similar to changes predicted for crop pests.

Design of Studies

Stem et al. (see Volume C) studied the available literature on four livestock diseases to evaluate the range of potential changes in disease distribution and occurrence under climate change conditions. Schmidtmann and Miller (see Volume C) used a population dynamics simulation model to estimate the effects of the GFDL climate change scenario on the life cycle of the horn fly, a ubiquitous pest of pastured cattle throughout the United States.

Limitations

The horn fly model is based on population counts taken at various times under different weather and management conditions. However, the prediction of current horn fly populations appears to be well correlated with observations. The model is not validated for the high temperatures predicted for the climate change. Schmidtmann and Miller used only the hottest climate change scenario, GFDL; the other scenarios may have resulted in a smaller geographic shift in the range of the horn fly. It should also be noted that the horn fly analysis is based on current livestock management, breeds, and distribution. Possible changes in these factors are beyond the scope of thus study. For example, changes in location and extent of grassland regions and forage production caused by climate warming would affect livestock production and horn fly distributions.

Results

Stem et al. found that under warmer conditions, livestock diseases currently causing serious economic losses in tropical countries could spread into the United States. Rift Valley fever is transmitted principally by mosquitoes, and the disease may spread as rising winter temperatures become able to support an increase in the mosquito population (see Figure 6-11). African swine fever also may become a greater threat.

The ranges and activities of disease-carrying agents of blue tongue and anaplasmosis, diseases currently causing severe losses in cattle and sheep production in the United States, may expand. If disease-carrying insects increase their winter survival and reproduce year-round in more states, the geographical distribution of blue tongue, which is caused by a virus, may expand northward and eastward. Anaplasmosis, a rickettsial infection of ruminants, is the second most important disease of cattle in the United States. Distribution of the insect carrier's habitat could expand to northern states with climate change, and the insects' day-today activity may increase; this process may also cause an increase in disease transmission.

The horn fly causes annual losses of $730.3 million in the beef and dairy cattle industries (Drummond, 1987). Schmidtmann and Miller found that with the very warm GFDL climate change scenario, the horn fly season throughout most of the United States could be extended by 8 to 10 weeks. The increase in horn fly populations could substantially reduce the average daily gain of growing beef cattle. Also under the GFDL. simulation, increased pest activity was estimated in dairy cattle in the North and Northwest -- a result that could significantly decrease milk production. Conversely, under the same scenario, the. summertime activity of the horn fly could decrease in the South because the warmer climate would exceed the horn fly's tolerance to high temperatures.

Implications

With climate change, patterns of livestock diseases and pests may also change. Tropical livestock diseases may become an increased threat, because more geographical areas are potential ranges for the insect carriers of the diseases. Temperature conditions may improve in the winter but may be exacerbated in the summer. Reproductive capabilities may be lower. Livestock production would also be affected if rangeland areas shift and forage production levels change.

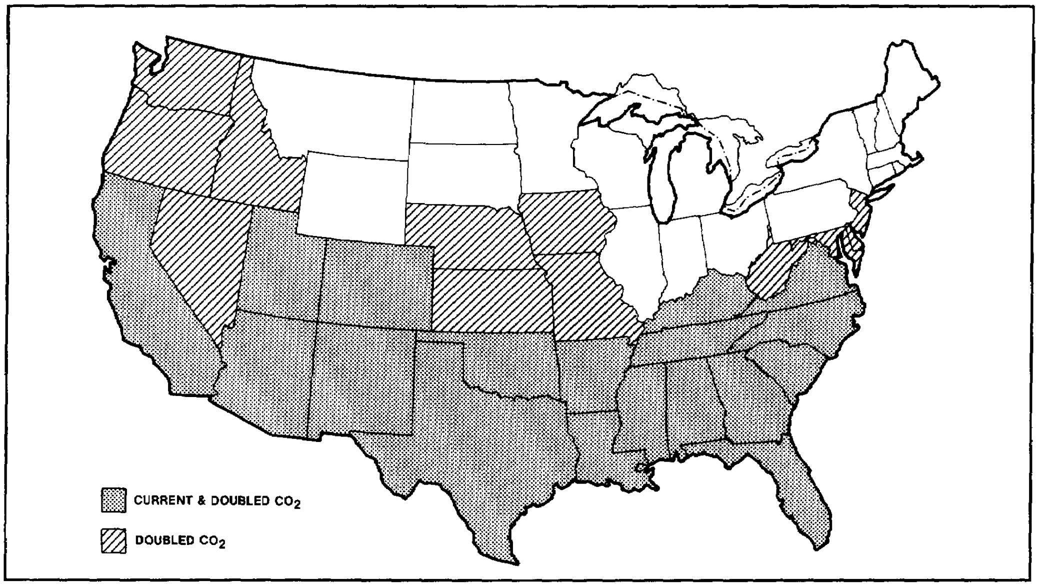


Figure 6-11. States where significant Culex app. activity permits establishment of Rift valley fever for current and doubled CO_2 levels (Stem, et al., Volume C).

ECONOMIC AND ECOLOGICAL IMPLICATIONS OF AGRICULTURAL STUDIES

The U.S. agricultural system has historically been able to adopt new technologies rapidly and may be less vulnerable to climate change than natural ecosystems. In fact, global warming may cause a number of benefits. Potential benefits of CO_2-induced climate change include increases in length of growing season and in air temperatures, which would benefit regions where crop growth is constrained by short summers and low temperatures. Longer growing seasons would likely lead to increased yields of hay and other perennial crops. Energy costs for grain drying may be reduced, since annual crops would reach maturity earlier and would have more opportunity to dry in the fields. Furthermore, in places where precipitation increases during the growing season, irrigation requirements could be reduced. If irrigation requirements are lessened, demand on regional water resources and associated costs to farmers may fall.

However, many reasons to avoid complacency about the predicted climate change remain. Concern for our major resources (especially land and water), rural communities, and the environment is justified. While many critical uncertainties exist regarding the magnitude and timing of impacts, it appears that climate change is likely to affect U.S. agriculture significantly in the coming century.

Costs and Timing of Adjustment

Since our agricultural production system primarily consists of specialized farms producing commodities in geographically specialized production patterns, the costs of adjusting to changed comparative advantage among agricultural regions, with ensuing changed resource use and changed agricultural infrastructure, may be quite **high in some regions.** These shifts would also entail involvement of and costs to the federal government.

If warming occurs rapidly, U.S. agriculture will have less time to adjust and costs may be greater. As climate continues to warm, costs may rise at an increasing rate. Finally, unless CO_2 and other trace gas emissions are limited, we may be facing a continual and possibly accelerating rate of atmospheric accumulations and climate change. As the agricultural system strives to adapt to a changing climate, there may be no chance of optimizing for static conditions. Rather, the system maybe caught in forever playing catch-up.

Effects of CO_2

It is also important to note that the crop modeling studies showed that the direct CO_2 effects on crop photosynthesis and water-use ehiciency ameliorate the negative effects of climate change in some locations under certain climate conditions; however, such effects do not occur uniformly, and they do not occur everywhere. Regional changes in U.S. agriculture occurred with the GISS and GFDL climate change scenarios both with and without the direct effects of CO_2. While much work must be done to improve both climate and crop models, policy analysis should consider that the beneficial direct effects of CO_2 may not offset the negative effects of climate change.

Environmental Quality

Changes in the agricultural production system are likely to have significant impacts on resource use and the environment. Many of the agricultural studies suggest that climate warming could result in accelerated rates of demand for water for irrigation (see Chapter 9: Water Resources), increases in pesticide usage to control changes in pest vectors, and changes in water quality from agricultural chemicals. Decreases in biological diversity may limit the adaptive capacity of agriculture, which requires a broad base of germ plasm for modifying current crops and developing new ones (see Chapter 8: Biodiversity).

A northward migration of agriculture would increase the use of irrigation and fertilizers on sandy soils, thus endangering underlying groundwater quality. From South Dakota to southern Canada, critical prairie wetlands may be lost to drainage and conversion to cropland. Many of these areas are important wildlife habitats. Shifts in agricultural activities may increase the susceptibility of soils to wind and water erosion. Climate change could thus exacerbate many of the current trends in environmental pollution and resource use associated with agriculture as well as initiate new ones.

Sea level rise, an associated impact of climate change, will threaten low-lying coastal agricultural regions with seasonal -- and in some instances permanent -- flooding, saltwater intrusion of freshwater aquifers and rivers, and salt contamination of soils. Agricultural lands in coastal regions may be lost. (See Chapter 9: Water Resources, and Chapter 7: Sea Level Rise, for linkages with agriculture.)

Furthermore, climate change will act on agriculture simultaneously with other environmental stresses. Levels of UV-B radiation caused by depletion of stratospheric ozone are likely to increase in the future, as are levels of tropospheric ozone and acid precipitation. The interactions among these multiple stresses and climate change need to be studied in agricultural settings.

Global Agriculture

Finally, US. agriculture is an integral part of the global, international agricultural system. Consequently, the adjustment of U.S. agriculture to climate change cannot be considered in isolation from the rest of the world. The optimal configuration of U.S. adjustments will depend very much on how simultaneous changes in regional climates affect global agriculture and how other countries, in turn, respond to those changes.

POLICY IMPLICATIONS

Since climate change appears likely to reconfigure the agricultural activities and demographics of rural America, policies should be examined in light of these potential effects. Agricultural policies should be designed to ease adjustments to climate change and to ensure the sustainability of our natural and human resources (see Schuh, Volume C, and Dudek, Volume C). Following are specific policy areas that policymakers could investigate to respond appropriately to the projected climate change.

Commodity Policies

Agricultural pricing and production policies should promote efficient adjustment to the changing conditions of global supply and demand induced by the greenhouse effect, which may include shifts in comparative advantage among regions and increased likelihood of droughts in some regions. Although these shifts may be slow, the cumulative effects may be large and they deserve close monitoring. Market forces as well as government programs would play a crucial role in creating the flexibility to respond to climate changes by sending signals on the efficient use of resources, and in mitigating their ultimate impact as they have done in the past. Agricultural policies should be evaluated to ensure that they are appropriate to both current and possible future conditions in regard to their ability to facilitate adaptation to climate change. For example, flexibility in shifting crop types and farm practices will speed adjustments.

Land-Use Programs

Federal legislation aimed at reducing the use of newly plowed grasslands, e.g., the "Sod-Buster Bill," and the related "Swamp-Buster Bill," which restricts agricultural encroachment into wetlands subject to flooding and water-logging, are examples of new policies meant to protect marginal lands. The basic goals of these new laws, which are part of the 1985 Farm Bill, are to protect the most erodible farmland by removing it from crop production and to use conservation as a tool for reducing overproduction. Nearly 80 million acres of U.S. cropland were retired under these and other farm programs in 1988. Policy research should address how these programs may fare under changing climate conditions.

Another program established in the 1985 Farm Bill that may help alleviate the negative effects of climate change is the Conservation Reserve Program. This program is aimed at removing from crop production the cropland classified as "highly erodible" by the Soil Conservation Service. The bill created a new form of long-term contract of up to 10 years and provides payments to farmers who apply conservation practices, such as maintaining a grass cover, on those acres. If successful, the Conservation Reserve Program may reduce the impact of climate fluctuations on total grain production by taking the most sensitive lands out of use.

The 1988 drought, however, demonstrated that the Conservation Reserve Program may be difficult to maintain in the face of climate stress. As the drought worsened during the summer, use of the set-aside lands was requested so that badly hit farmers could salvage some economic benefits from these acres. Such conflicts may be more common in the future, and land retirement strategies must be weighed against possible needed increases in production.

Awareness of potential changes in agricultural land use due to regional climate change should be built into land-use planning programs, especially in regions where agricultural activities may expand into natural, unmanaged ecosystems. Large-scale drainage and water projects would need environmental impact studies to carefully assess this potential expansion of agricultural land (see Baldwin, Volume J).

Water-Resource Management Programs

Current water supply policies do not generally encourage optimum water-use efficiency. A greater degree of water efficiency should promote flexibility in light of the potential for increased irrigation demands with climate change. Policies such as water transfers and markets should be considered for irrigated areas.

Water Quality Policy

The increased use of agricultural chemicals, along with changes in the hydrological cycle, potentially threaten both soil and water supplies, and eventually, public health. Negative consequences could be avoided or lessened by including potential climate change effects in water quality planning and by supporting alternative pest management strategies that use such techniques as biological control, genetic resistance, and innovative cropping systems.

Risk Management and Drought Policy

Changes in the frequency, intensity, and location of extreme events are important for agriculture and the regional income that it produces. The adequacy of the private crop insurance and federal disaster payment programs should be assessed in the face of climatic uncertainty. For example, only about 20 to 25% of potentially insurable acreage is currently covered by crop insurance. Farmers tend to rely on federal disaster relief programs to bail them out of such disasters as droughts, floods, hail, and windstorms. Financial risk is also part of the credit structure that covers land, equipment, and production in modern farming.

The frequency and magnitude of climate extremes may be altered with climate change. Responding to the changes may be costly for the government if crops fail frequently. The Drought Relief

Bill for the drought of 1988 is scheduled to cost $3.9 billion to cover just 1 year of a climatic extreme. On the other hand, some areas that currently suffer from climate extremes may benefit from climate change. Risk policy mechanisms for relief, recovery, and mitigation of climate change should be examined so that they will be ready to help farmers adjust.

A national drought policy is strongly needed to coordinate federal response to the possibility of increased frequency and duration of future droughts due to climate change. Even without climate change, such a policy is needed not only for the agricultural sector but also for other sectors.

International Trade Agreements

Policies designed to ease the adjustment to greenhouse effects must be global in scope because the effects, although varied, are global in nature. Comparative advantage will likely shift significantly both within the United States and in other countries. Population and economic activities also would change geographically with climate change, thus affecting the location of demand for agricultural products. It is already a goal of U.S. agricultural policy to incorporate global conditions of supply and demand into the agricultural sector. The potential seriousness of the impacts on the agricultural production system of the greenhouse effect may provide added incentive to establish such policies both nationally and internationally. The vulnerability of current and potential food-deficit regions to climate change should also be considered.

Agricultural Contributions to the Greenhouse Effect

Agriculture itself is an active contributor to the greenhouse effect. Clearing of forested land for agriculture often involves burning of trees and shrubs that release CO_2. The biomass that is not burned tends to decay gradually, also emitting CO_2. Agricultural activities release other radiatively active trace gases. Flooded rice fields emit methane (CH4) as a product of the anaerobic decomposition of organic matter. Ruminants also release methane as a consequence of their digestive processes. In addition, soils may volatilize some of the nitrogenous fertilizer applied to them in the form of nitrous oxide (N_20). Finding effective ways to reduce these emissions presents a major challenge to the agricultural research community. In this regard, the Conservation Reserve Program and forestation efforts could provide a partial solution, since vegetation fixes CO_2 from the air. (See Lashof and Tirpak, 1989, for further discussion of agriculture's contribution to the greenhouse effect.)

Agricultural Research

The agricultural research community should enhance climate change research from the field level to the national policy level. It should continue to breed heat- and drought-resistant crop varieties and new crop species in preparation for global warming. Research in biotechnology may also be directed toward alleviating the negative effects of climate change. Improved water-use and irrigation efficiency also take on renewed importance in the light of potential climate change. Energy requirements of the agricultural system under climate change should be defined, given the potential for increases in energy-intensive activities such as irrigation and application of agricultural chemicals. Research attention also should be directed toward reducing agricultural emissions of trace gases.

RESEARCH NEEDS

1. <u>International agriculture</u> -- Study the potential shifts in international comparative advantage and the vulnerability of fooddeficit regions, and evaluate the implications of such shifts for the United States.

   One of the most crucial areas for further research is the projection of potential climate change effects at the international level. Potential changes in agricultural yields and production of major crops, and impacts on regions that are food-deficient now or that may become food-deficient in the future, all need to be studied. Economics and policy research should consider the implications of shifts in global agriculture for the levels of U.S. crop exports and the role of the United States as a reliable supplier of agricultural export commodities.

2. Crop and livestock productivity -- Study the interactive effects of climate variability and change, CO_2, tropospheric ozone, UV-B from stratospheric ozone depletion, and other environmental and societal variables on agricultural productivity. Determine how changed climatic variability may amplify or lessen the preliminary EPA results.

   Because of the significant production changes indicated by these studies, the need for better simulation of the direct effects of CO_2 in the crop models, and the limited adjustment studies performed, further crop research should be conducted on a longer term basis. Necessary work includes resolving the differences in forecasts of the GCMs, and designing more appropriate scenarios including transient climate change and changes in climatic variability. Physiologically based submodels are needed for the effects of increased CO_2 on various crops. The effects on other major crops such as cotton also should be studied. Crop models should be improved in their simulation of the effects of increasing temperatures.

   Research on the direct CO_2 effects on crops to this point has provide windows of knowledge concerning certain crops at specific stages of their life cycles. Both the direct and the climate change effects of high CO_2 are probably quite different at different stages of development. Research should evaluate the interactive effects of CO_2 and temperature over the whole life cycle of the plant, with varying conditions of water and nutrition, rather than with plants under optimal conditions. Then crop response to the combined climatic and physiological effects of CO_2 may be predicted more realistically. Much more research on climate change and livestock production is needed. Important research areas include crop-livestock interactions, reproduction, and diseases.

3. Adaptation strategies -- Study the dynamic nature of climate change: What is the rate of adaptation of regional agricultural systems compared with the rate of climate change? Evaluate the thresholds of sensitivity of U.S. agriculture. Studies should analyze the ability of various aspects of the agricultural production systems to adapt to various rates and degrees of climate change to determine these thresholds of sensitivity. It would also be useful to identify the costs of different types of adjustments and the regions most likely to experience greater costs.

4. Agricultural economics -- Expand the national analysis to include crops and regions not now included (for example, cotton and grasslands, and the western regions of the United States). Conduct further analyses of regional shifts in agriculture. Studies that link water resource and agriculture models are needed to estimate changes in water demand among agriculture and competing users. Thus, estimates of actual changes in irrigated acreage could be made.

5. Environmental impacts -- Elucidate the impacts of climate change on water quantity, water quality, and other components of the environment caused by shifts in crop and livestock production and related industries.

6. Agricultural emissions of trace gases -- Discover effective ways to reduce emissions of methane from livestock, nitrous oxide from fertilizer application, and other agricultural sources of trace gases.

REFERENCES

Acock, B., and L.H. Allen, Jr. 1985. Crop responses to elevated carbon dioxide concentrations. In: Strain, B.R., and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238. pp.33-97.

Adams, R.M., S.A. Hamilton, and B.A. McCarl. 1984. The Economic Effects of Ozone on Agriculture. Corvallis, OR: U.S. Environmental Protection Agency. EPA-600/3-84-090.

Awes, David R. 1981. Effect of climate on livestock production data. In: Knapp, F.W., ed. Systems Approach to Animal Health and Production. Lexington, KY: University of Kentucky. pp.148-148.

Callaway, J.M., F.J. Cronin, J.W. Currie, and J. Tawil. 1982. An analysis of methods and models for assessing the direct and indirect impacts of CO_2 induced environmental changes in the agricultural sector of the U.S. economy. Richland, WA: Pacific Northwest Laboratory, Battelle Memorial Institute. PNL-4384.

Carbon Dioxide Assessment Committee. 1983. Changing Climate. Washington, DC: National Academy of Sciences.

Carsel, R.F., C.N. Smith, LA. Mulkey, J.D. Dean, and P. Jowise. 1984. Users Manual for the Pesticide Root Zone Model (PRZM). Athens, GA: U.S. Environmental Protection Agency. EPA600/3-84-109.

Council for Agricultural Science and Technology. 1988. Long-Term Viability of U.S. Agriculture. Ames, IA: Council for Agricultural Science and Technology. Report No. 114.

Cure, J.D. 1985. Carbon dioxide doubling responses: A crop survey. In: Strain, B.R., and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238. pp. 99116.

Decker, W.L., V. Jones, and R. Achutuni. 1985. The impact of CO_2 induced climate change on U.S. agriculture. In: White, M.R., ed. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. DOE/ER-0236. pp. 69-93

Dudek, D.J. 1987. Economic implications of climate change impacts on southern agriculture. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues. Norman, OK: University of Oklahoma, Science and Public Policy Program. pp. 44-72.

Drummond, R.O. 1987. Economic aspects of ectoparasites of cattle in North America. In: Leaning, W.H.D., and J. Guerrero, eds. Proceedings of the MSD AGVET Symposium, The Economic Impact of Parasitism in Cattle. XXIII. World Veterinary Congress. Montreal, Quebec. pp. 9-24.

Hansen, J., I. Fung, A. Lacis, D. Rind, G. Russell, S. Lebedeff, R. Ruedy, and P. Stone. 1988. Global climate changes as forecast by the GISS 3-D model. Journal of Geophysical Research 93(D8):9341-9364.

Jones, C.A., and J.R. Kiniry, eds. 1986. CERESMaize: A Simulation Model of Maize Growth and Development. College Station, TX: Texas A&M University Press.

Jones, J.W., K.J. Boote, S.S. Jagtap, G. Hoogenboom, and G.G. Wilkerson. 1988. SOYGRO V5.41: Soybean Crop Growth Simulation Model. User's Guide. Florida Agr. Exp. Sta. Journal No. 8304, IFAS. Gainesville, FL: University of Florida.

Jones, J.W., J.W. Mishoe, G. Wilkerson, J.L. Stimac, and W.G. Boggess. 1986. Integration of soybean crop and pest models. In: Frisbie, P.E., and P. Adisson, eds. Integrated Pest Management on Major Agriculture Systems. Texas Agriculture Experiment Station. Publication No. MP-1616. College Station, TX: Texas A&M University.

Kimball, B.A. 1985. Adaptation of vegetation and management practices to a higher carbon dioxide world. In: Strain, B.R., and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238. pp. 185-204.

Land Evaluation Group. 1987. Implications of climatic warming for Canada's comparative position in agricultural production and trade. Guelph, Ontario: University of Guelph, University School of Rural Planning and Development.

Lashof, D., and D. Tirpak, eds. 1989. Policy Options for Stabilizing Global Climate. Draft report. Washington, DC: U.S. Environmental Protection Agency.

Parry, M.L., T.R. Carter, N.T. Konijn, eds. 1988. The Impact of Climatic Variations on Agriculture. Vol. 1. Assessments in Cool Temperate and Cold Regions. Dordrecht: Kluwer.

Postel, S. 1986. Altering the Earth's Chemistry:

Assessing the Risks. Worldwatch Paper 71. Washington, DC: Worldwatch Institute.

Ritchie, J.T., and S. Otter. 1985. Description and performance of CERES-Wheat: A user-oriented wheat yield model. In: Willis, W.O., ed. ARS Wheat Yield Project. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service. ARS-38. pp. 159-175.

Schneider, K. 1988. Drought cutting U.S. grain crop 31% this year. The New York Times August 12:A 1.

USDA. 1976. U.S. Department of Agriculture. Handbook of Agricultural Charts. Agricultural Handbook 504. Washington, DC: U.S. Government Printing Office.

USDA. 1987. U.S. Department of Agriculture. Agricultural Statistics. Washington, DC: U.S. Government Printing Office.

U.S. Department of Commerce. 1983. U.S. Department of Commerce, Bureau of the Census. 1982 Census of Agriculture, Vol. 1. Geographical Area Series, Part 51, United States Summary and State Data. Washington, DC: U.S. Government Printing Office.

Warrick, R.A., R.M. Gifford, M.L. Parry. 1986. CO_2, climatic change and agriculture. Assessing the response of food crops to the direct effects of increased CO_2 and climatic change. In: Bolin, B., B.R. Doos, J. Jager, and R.A. Warrick, eds. The Greenhouse Effect, Climatic Change and Ecosystems. A Synthesis of the Present Knowledge, SCOPE 29. New York: John Wiley and Sons. pp. 393-473.

Webster, A.J.F. 1981. Weather and infectious disease in cattle. The Veterinary Record 108:183187.

World Food Institute. 1987. World Food Trade and U.S. Agriculture, 1960-1986. Ames, IA: Iowa State University.

Zachariah, K.C., and Vu, M.T. World Bank. 1988. World Population Projections. 1987-1988 Ed. Shortand Long-Term Estimates. Baltimore, MD: Johns Hopkins University Press.

CHAPTER 7
SEA LEVEL RISE

FINDINGS

Global warming could cause sea level to rise 0.5 to 2 meters by 2100. Such a rise would inundate wetlands and lowlands, erode beaches, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

- A 1-meter rise could drown approximately 25 to 80% of the U.S. coastal wetlands; ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads blocked their migration. Even current sea level trends threaten the wetlands of Louisiana.

- A 1-meter rise could inundate 5,000 to 10,000square miles of dryland if shores were not protected and 4,000 to 9,000 square miles of dryland if only developed areas were protected.

- Most coastal barrier island communities would probably respond to sea level rise by raising land with sand pumped from offshore. Wide and heavily urbanized islands may use levees, while communities on lightly developed islands may adjust to a gradual landward migration of the islands.

- Protecting developed areas against such inundation and erosion by building bulkheadsand levees, pumping sand, and raising barrier islands could cost $73 to $111 billion (cumulative capital costs in 1985 dollars) for a 1-meter rise by the year 2100 (compared with $6 to $11 billion under current sea level trends). Of this total, $50 to $75 billion would be spent (cumulative capital costs in 1985 dollars) to elevate beaches, houses, land, and roadways by the year 2100 to protect barrier islands (compared with $4 billion under current trends). Developed barrier islands would likely be protected from sea level rise because of their high property values.

- The Southeast would bear approximately 90% of the land loss and 66% of the shore protection costs.

Policy Implications

- Many of the necessary responses to sea level rise, such as rebuilding ports, constructing levees, and pumping sand onto beaches, need not be implemented until the rise is imminent. On the other hand, the cost of incorporating sea level rise into a wide variety of engineering and land use decisions would be negligible compared with the costs of not responding until sea level rises.

- Many wetland ecosystems are likely to survive sea level rise only if appropriate measures are implemented in the near future. At the state and local levels, these measures include land use planning, regulation, and redefinitions of property rights. The State of Maine has already issued regulations to enable wetlands to migrate landward by requiring that structures be removed as sea level rises.

- The coastal wetlands protected under Section 404 of the Clean Water Act will gradually be inundated. The act does not authorize measures to ensure survival of wetland ecosystems as sea level rises.

- The National Flood Insurance Program may wish to consider the implications of sea level rise on its future liabilities. A recent HUD authorization act requires this program to purchase property threatened with erosion. The act may imply a commitment by the federal government to compensate property owners for losses due to sea level rise.

- The need to take action is particularly urgent in coastal Louisiana, which is already losing 100 square kilometers per year.

CAUSES, EFFECTS, AND RESPONSES

Global warming from the greenhouse effect could raise sea level approximately 1 meter by expanding ocean water, melting mountain glaciers, and causing ice sheets in Greenland to melt or slide into the oceans. Such a rise would inundate coastal wetlands and lowlands, erode beaches, increase the risk of flooding, and increase the salinity of estuaries, aquifers, and wetlands.

In the last 5 years, many coastal communities throughout the world have started to prepare for the possibility of such a rise. In the United States, Maine has enacted a policy declaring that shorefront buildings will have to be moved to enable beaches and wetlands to migrate inland to higher ground. Maryland has shifted its shore-protection strategy from a technology that can not accommodate sea level rise to one that can. Seven coastal states have held large public meetings on how to prepare for a rising sea. Australia, the Netherlands, and the Republic of Maldives are beginning to undergo a similar process.

Causes

Ocean levels have always fluctuated with changes in global temperatures. During the ice ages when the earth was 5°C (9°F) colder than today, much of the ocean's water was frozen in glaciers and sea level often was more than 100 meters (300 feet) below the present level (Dorm et al., 1962; Kennett, 1982; Oldale, 1985). Conversely, during the last interglacial period (100,000 years ago) when the average temperature was about 1°C (2°F) warmer than today, sea level was approximately 20 feet higher than the current sea level (Mercer, 1968).

When considering shorter periods of time, worldwide sea level rise must be distinguished from relative sea level rise. Although climate change alters worldwide sea level, the rate of sea level rise relative to a particular coast has greater practical importance and is all that monitoring stations can measure. Because most coasts are sinking (and a few are rising), the range of relative sea level rise varies from more than 3 feet per century in Louisiana and parts of California and Texas to 1 foot per century along most of the Atlantic and gulf coasts, to a slight drop in much of the Pacific Northwest (Figure 7-1). Areas such as Louisiana provide natural laboratories for assessing the possible effects of future sea level rise (Lyle et al., 1987).

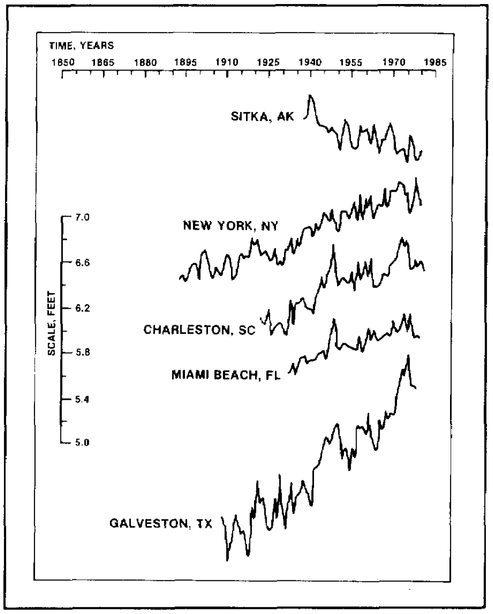


Figure 7-1. Time series graph of sea level trends for New York, Charleston, Miami, Galveston, and Siika (Lyle et al., 1987).

Global sea level trends have generally been estimated by combining the trends at tidal stations around the world. Studies combining these measurements suggest that during the last century, worldwide sea level has risen 10 to 15 centimeters (4 to 6 inches) (Barnett, 1984; Fairbridge and Krebs, 1962). Much of this rise has been attributed to the global warming that has occurred during the last century (Meier, 1984; Gornitz et al., 1982). Hughes (1983) and Bentley (1983) estimated that a complete disintegration of West Antarctica in response to global warming would require a 200- to 500-year period, and that such a disintegration would raise sea level 20 feet. Most recent assessments, however, have focused on the likely rise by the year 2100. Figure 7-2 illustrates recent estimates of sea level rise, which generally fall into the range of 50 io 200 centimeters.

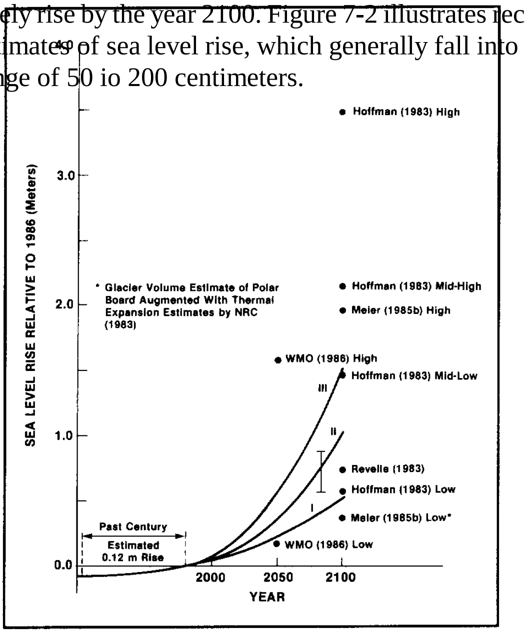


Figure 7-2. Estimates of future sea level rise (derived from Hoffman, 1983, 1986; Meier, 1985; Revelle, 1983).

Although most studies have focused on the impact of global warming on global sea level, the greenhouse effect would not necessarily raise sea level by the same amount everywhere. Removal of water from the world's ice sheets would move the earth's center of gravity away from Greenland and Antarctica and would thus redistribute the oceans' water toward the new center of gravity. Along the U.S. coast, this effect would generally increase sea level rise by less than 10%. Sea level could actually drop, however, at Cape Horn and along the coast of Iceland. Climate change could also affect local sea level by changing ocean currents, winds, and atmospheric pressure; no one has estimated these impacts.

Effects

In this section and in the following sections, the effects of and responses to sea level rise are presented separately. However, the distinction is largely academic and is solely for presentation purposes. In many cases, the responses to sea level rise are sufficiently well established and the probability of no response is sufficiently low that it would be misleading to discuss the potential effects without also discussing responses. For example, much of Manhattan Island is less than 2 meters above high tide; the effect of sea level rise would almost certainly be the increased use of coastal engineering structures and not the inundation of downtown New York.

A rise in sea level would inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, raise water tables, and increase the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). Most of the wetlands and lowlands are found along the gulf coast and along the Atlantic coast south of central New Jersey, although a large area also exists around San Francisco Bay. Similarly, the areas vulnerable to erosion and flooding are also predominately in the Southeast; potential salinity problems are spread more evenly along the U.S. Atlantic coast. We now discuss some of the impacts that would result if no responses were initiated to address sea level rise.

Destruction of Coastal Wetlands

Coastal wetlands are generally found between the highest tide of the year and mean sea level. Wetlands have kept pace with the past rate of sea level rise because they collect sediment and produce peat upon which they can build; meanwhile, they expanded inland as lowlands were inundated (Figure 7-3). Wetlands accrete vertically and expand inland. Thus, as Figure 7-3 illustrates, the present area of wetlands is generally far greater than the area that would be available for new wetlands as sea level rises (Titus et al., 1984b; Titus, 1986). The potential loss would be the greatest in Louisiana (see Chapter 16: Southeast).

In many areas, people have built bulkheads just above the marsh. If sea level rises, the wetlands will be squeezed between the sea and the bulkheads (see Figure 7-3). Previous studies have estimated that if the development in coastal areas were removed to allow new wetlands to form inland, a 1.5- to 2-meter rise would destroy 30 to 70% of the U.S. coastal wetlands. If levees and bulkheads were erected to protect today's dryland, the loss could be 50 to 80% (Titus, 1988; Armentano et al., 1988).

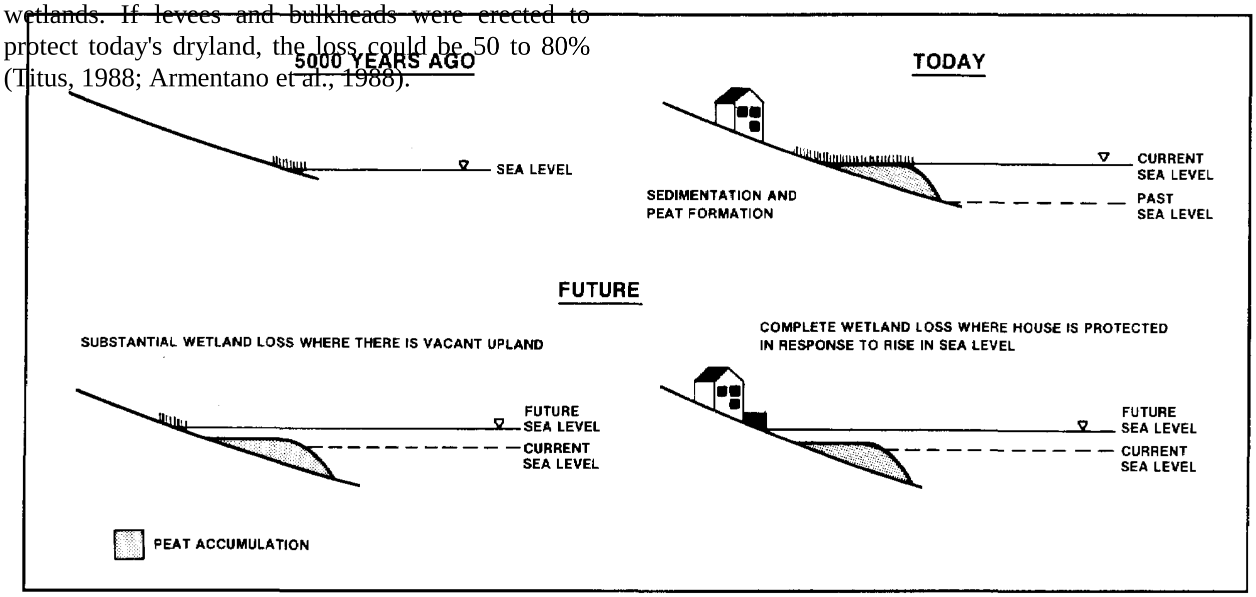


Figure 7-3. Evolution of marsh as sea rises. Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands have been inundated. If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract. Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas.

Such a loss would reduce the available habitat for birds and juvenile fish and would reduce the production of organic materials on which estuarine fish rely.

The dryland within 2 meters of high tide includes forests, farms, low parts of some port cities, cities that sank after they were built and are now protected with levees, and the bay sides of barrier islands. The low forests and farms are generally in the mid-Atlantic and Southeast regions; these would provide potential areas for new wetland formation. Major port cities with low areas include Boston, New York, Charleston, and Miami. New Orleans is generally 8 feet below sea level, and parts of Galveston, Texas City, and areas around the San Francisco Bay are also well below sea level. Because they are already protected by levees, these cities are more concerned with flooding than with inundation.

Inundation and Erosion of Beaches and Barrier Islands

Some of the most important vulnerable areas are the recreational barrier islands and spits (peninsulas) of the Atlantic and gulf coasts. Coastal barriers are generally long narrow islands and spits with the ocean on one side and a bay on the other. Typically, the oceanfront block of an island ranges from 5 to 10 feet above high tide, and the bay side is 2 to 3 feet above high water. Thus, even a 1meter sea level rise would threaten much of this valuable land with inundation.

Erosion threatens the high part of these islands and is generally viewed as a more immediate problem than the inundation of the bay sides. As Figure 7-4 shows, a rise in sea level can cause an ocean beach to retreat considerably more than it would from the effects of inundation alone. The visible part of the beach is much steeper than the underwater portion, which comprises most of the active "surf zone." While inundation alone is determined by the slope of the land just above the water, Bruun (1962) and others have shown that the total shoreline retreat from a sea level rise depends on the average slope of the entire beach profile.

Previous studies suggest that a 1-foot rise in sea level would generally cause beaches to erode 50 to 100 feet from the Northeast to Maryland (e.g., Kyper and Sorensen, 1985; Everts, 1985); 200 feet along the Carolinas (Kana et al., 1984); 100 to 1,000 feet along the Florida coast (Bruun, 1962); 200 to 400 feet along the California coast (Wilcoxen, 1986); and perhaps several miles in Louisiana. Because most U.S. recreational beaches are less than 100 feet wide at high tide, even a 1-foot rise in sea level would require a response. In many areas, undeveloped barrier islands could keep up with rising sea level by "over-washing" landward. In Louisiana, however, barrier islands are breaking up and exposing the wetlands behind them to gulf waves; consequently, the Louisiana barrier islands have rapidly eroded.

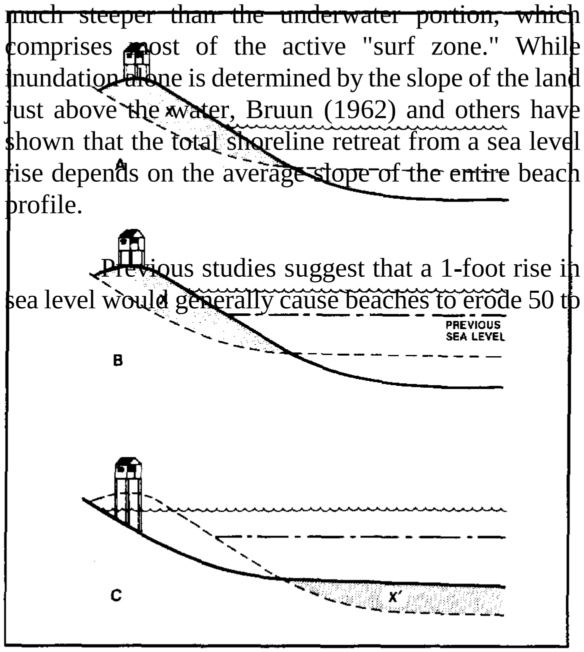


Figure 7-4. The Bruun Rule: (A) initial condition; (B) immediate inundation when sea level rises; (C) subsequent erosion due to sea level rise. A rise in sea level immediately results in shoreline retreat due to inundation, shown in the first two examples. However, a 1-meter rise in sea level implies that the offshore bottom must also rise 1 meter. The sand required to raise the bottom (X') can be supplied by beach nourishment. Otherwise, waves will erode the necessary sand (X) from upper part of the beach as shown in (C).

<u>Flooding</u>

If sea level rises, flooding would increase along the coast for four reasons: (1) A higher sea level provides a higher base for storm surges to build upon. A 1-meter sea level rise would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm (e.g., Kana et al., 1984; Leatherman, 1984). (2) Beach erosion also would leave oceanfront properties more vulnerable to storm waves. (3) Higher water levels would reduce coastal drainage and thus would increase flooding attributable to rainstorms. In artificially drained areas such as New Orleans, the increased need for pumping could exceed current capacities. (4) Finally, a rise in sea level would raise water tables and would flood basements, and in cases where the groundwater is just below the surface, perhaps raise it above the surface.

<u>Saltwater Intrusion</u>

A rise in sea level would enable saltwater to penetrate farther inland and upstream into rivers, bays, wetlands, and aquifers. Salinity increases would be harmful to some aquatic plants and animals, and would threaten human uses of water. For example, increased salinity already has been cited as a factor contributing to reduced oyster harvests in the Delaware and Chesapeake Bays, and to conversion of cypress swamps to open lakes in Louisiana. Moreover, New York, Philadelphia, and much of California's Central Valley obtain their water from areas located just upstream from areas where the water is salty during droughts. Farmers in central New Jersey and the city of Camden rely on the Potomac-Raritan-Magothy Aquifer, which could become salty if sea level rises (Hull and Titus, 1986). The South Florida Water Management District already spends millions of dollars every year to prevent Miami's Biscayne Aquifer from becoming contaminated with seawater.

Responses

The possible responses to inundation, erosion, and flooding fall broadly into three categories: erecting walls to hold back the sea, allowing the sea to advance and adapting to the advance, and raising the land. Both the slow rise in sea level over the last thousand years and the areas where land has been sinking more rapidly offer numerous historical examples of all three responses.

For over five centuries, the Dutch and others have used dikes and windmills to prevent inundation from the North Sea. By contrast, many cities have been rebuilt landward as structures have eroded; the town of Dunwich, England, has rebuilt its church seven times in the last seven centuries. More recently, rapidly subsiding communities (e.g., Galveston, Texas) have used fill to raise land elevations; the U.S. Army Corps of Engineers and coastal states regularly pump sand from offshore locations to counteract beach erosion. Venice, a hybrid of all three responses, has allowed the sea to advance into the canals, has raised some lowlands, and has erected storm protection barriers.

Most assessments in the United States have concluded that low-lying coastal cities would be protected with bulkheads, levees, and pumping systems, and that sparsely developed areas would adapt to a naturally retreating shoreline (e.g., Dean et al., 1987; Gibbs, 1984; Schelling, 1983). This conclusion has generally been based on estimates that the cost of structural protection would be far less than the value of the urban areas being protected but would be greater than the value of undeveloped land.

Studies on the possible responses of barrier islands and moderately developed mainland communities show less agreement but generally suggest that environmental factors would be as important as economics. Some have suggested that barrier islands should use seawalls and other "hard" engineering approaches (e.g., Kyper and Sorensen, 1985; Sorensen et al., 1984). Others have pointed to the esthetic problems associated with losing beaches and have advocated a gradual retreat from the shore (Howard et al., 1985). Noting that new houses on barrier islands are generally elevated on pilings, Titus (1986) suggested that communities could hold back the sea but keep a natural beach by extending the current practice of pumping sand onto beaches to raising entire islands in place.

Responses to erosion are more likely to have adverse environmental impacts along sheltered water than on the open coast (Titus, 1986). Because the beach generally is a barrier island's most important asset, economics would tend to encourage these communities to preserve their natural shorelines; actions that would prevent the island from breaking up also would protect the adjacent wetlands. However, along most mainland shorelines, economic self-interest would encourage property owners to erect bulkheads; these would prevent new wetland formation from offsetting the loss of wetlands that were inundated.

Most of the measures for counteracting saltwater intrusion attributable to sea level rise have also been employed to address current problems. For example, the Delaware River Basin Commission protects Philadelphia's freshwater intake on the river and New Jersey aquifers recharged by the river by storing water in reservoirs during the wet season and releasing it during droughts, thereby forcing the saltwater back toward the sea. Other communities have protected coastal aquifers by erecting underground barriers and by maintaining freshwater pressure through the use of impoundments and injection wells.

HOLDING BACK THE SEA: A NATIONAL ASSESSMENT

The studies referenced in the previous section have illustrated a wide variety of possible effects from and responses to a rise in sea level from the greenhouse effect. Although they have identified the implications of the risk of sea level rise for specific locations and decisions, these studies have not estimated the nationwide magnitude of the impacts. This report seeks to fill that void.

It was not possible to estimate the nationwide value of every impact of sea level rise. The studies thus far conducted suggest that the majority of the environmental and economic costs would be associated with shoreline retreat and measures to hold back the sea, which can be more easily assessed on a nationwide basis. Because the eventual impact will depend on what people actually do, a number of important questions can be addressed within this context:

- Would a gradual abandonment of moderately developed mainland areas significantly increase the amount of wetlands that survived a rise in sea level?

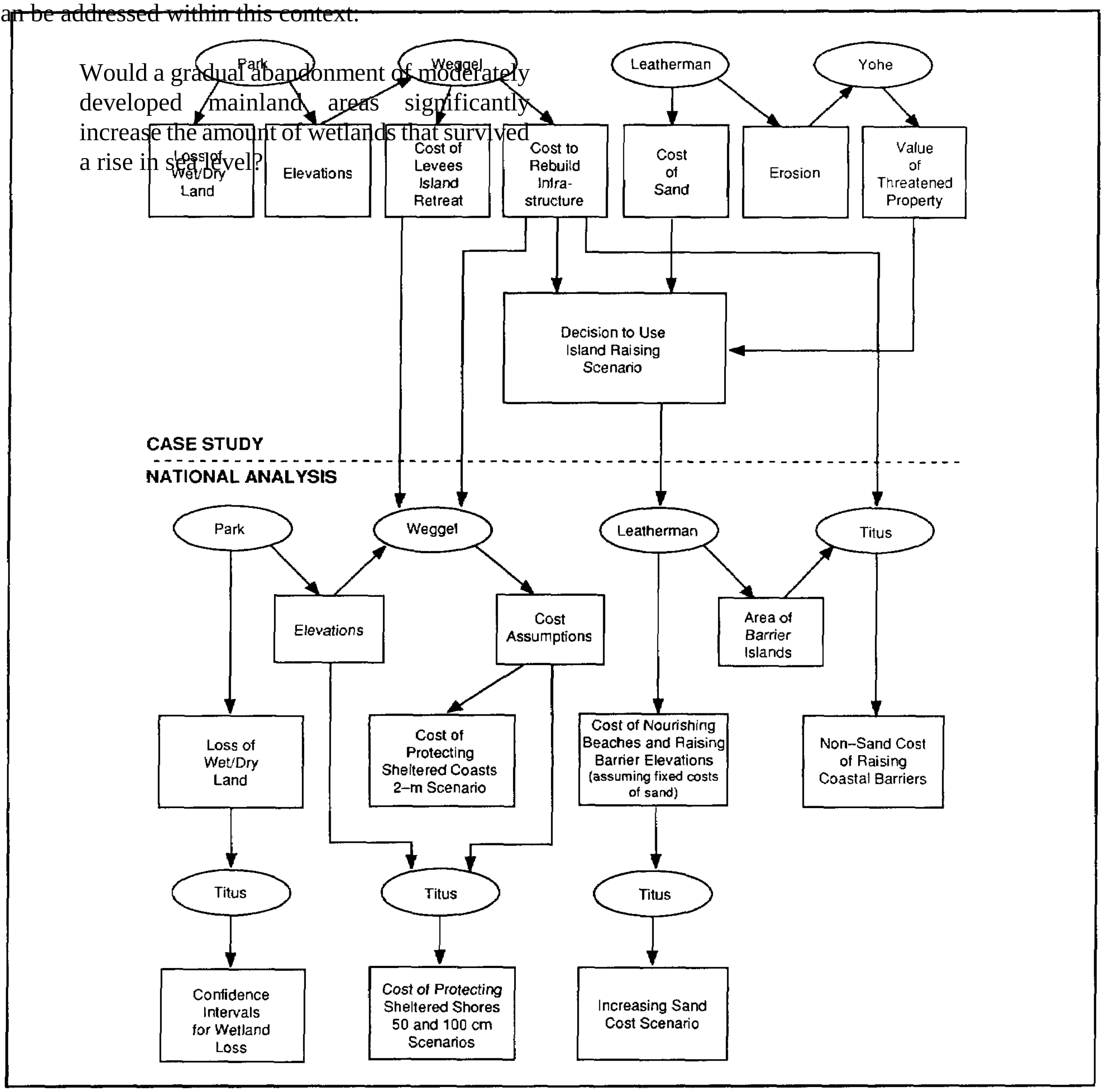


Figure 7-5. Overview of sea level rise studies and authors.

- Would the concave profiles of coastal areas ensure that more wetlands would be lost than gained, regardless of land-use decisions?

- Should barrier islands be raised in place by pumping sand and elevating structures and utilities?
- Would a landward migration of developed barrier islands or encircling them with dikes and levees be feasible alternatives?
- How much property would be lost if barrier islands were abandoned?

STRUCTURE OF STUDIES FOR THIS REPORT

A central theme underlying these questions is that the implications of sea level rise for a community depend greatly on whether people adjust to the natural impact of shoreline retreat or undertake efforts to hold back the sea. Because no one knows the extent to which each of these approaches would be applied, this study was designed to estimate the impacts of sea level rise for (1) holding back the sea, and (2) natural shoreline retreat.

The tasks were split into five discrete projects:

1. Park et al. estimated the loss of coastal wetlands and dryland.

2. Leatherman estimated the cost of pumping sand onto open coastal beaches and barrier islands.

3. Weggel et al. estimated the cost of protecting sheltered shores with levees and bulkheads.

4. Yohe began a national economic assessment by estimating the value of threatened property.

5. Titus and Greene synthesized the results of other studies to estimate ranges of the nationwide impacts.

Figure 7-5 illustrates the relationships between the various reports. (All of the sea level rise studies are in Volume B of the Appendices to this report.) As the top portion shows, the assessment began with a case study of Long Beach Island, New Jersey, which was necessary for evaluating methods and providing data for purposes of extrapolation. The Park and Leatherman studies performed the same calculations for the case study site that they would subsequently perform for the other sites in the nationwide analysis. However, Weggel and Yohe conducted more detailed assessments of the case study whose results were used in the Leatherman and Titus studies.

Because it would not be feasible for Leatherman to examine more than one option for the cost of protecting the open coast, Weggel estimated the cost of protecting Long Beach Island by three approaches: (1) raising the island in place; (2) gradually rebuilding the island landward; and (3) encircling the island with dikes and levees. Yohe estimated the value of threatened structures. Titus analyzed Weggel's and Yohe's results and concluded that raising barrier islands would be the most reasonable option for the Leatherman study and noted that the cost of this option would be considerably less than the resources that would be lost if the islands were not protected as shown in Figure 7-6.

Once the case study was complete, Park, Leatherman, and Weggel proceeded independently with their studies (although Park provided Weggel with elevation data). When those studies were complete, Titus synthesized their results, developing a nationwide estimate of the cost of holding back the sea and interpolating Weggel's 200-centimeter results for the 50- and 100centimeter scenarios.

In presenting results from the Park and Weggel studies, the sites were grouped into seven coastal regions, four of which are in the Southeast: New England, mid-Atlantic, south Atlantic, south Florida/gulf coast peninsula, Louisiana, other gulf (Texas, Mississippi, Alabama, Florida Panhandle), and the Pacific coast. Figure 7-7 illustrates these regions.

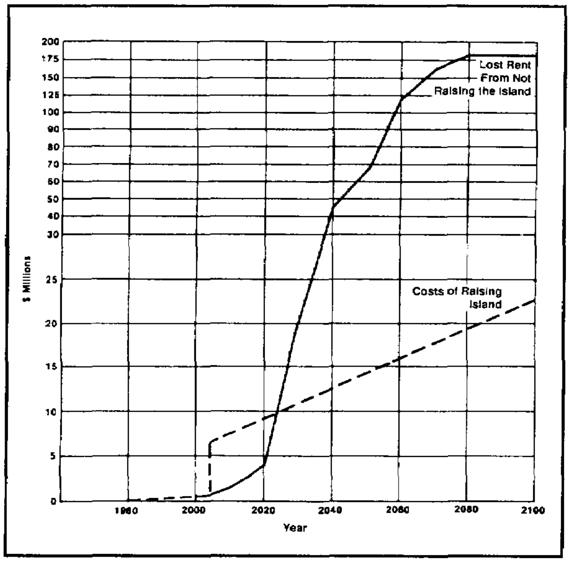


Figure 7-6. Annual cost of raising island versus annual costs (lost rent) from not protecting the island (in 1986 dollars) (Titus and Greene, Volume B).

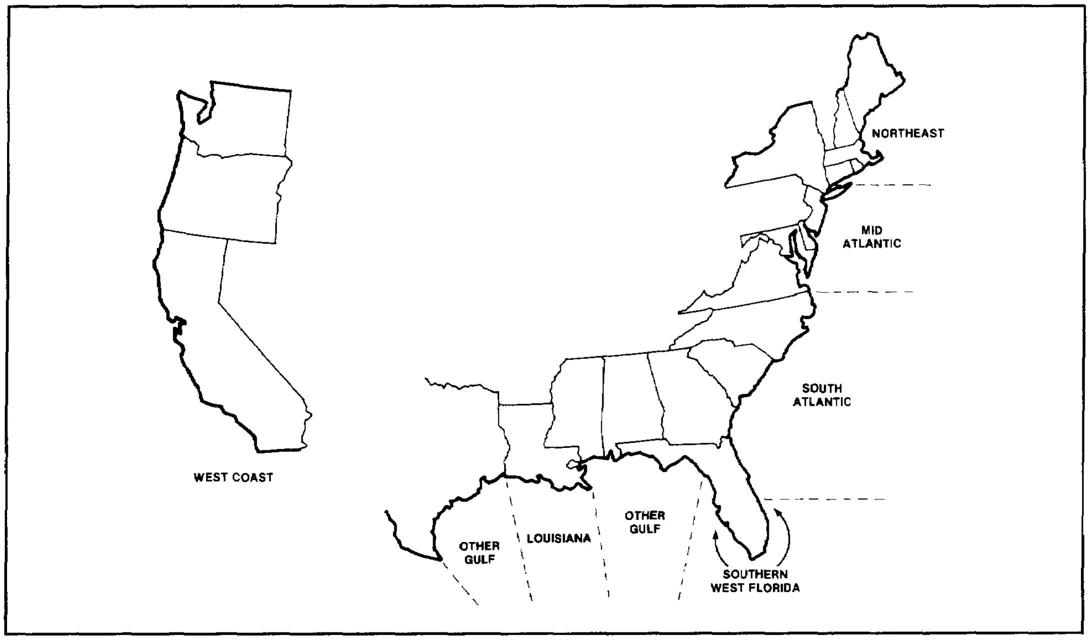


Figure 7-7. Costal regions used in this study.

SCENARIOS OF SEA LEVEL RISE

Although the researchers considered a variety of scenarios of future sea level rise, this report focuses on the impacts of three scenarios: rises of 50, 100, and 200 centimeters by the year 2100. All three of these scenarios are based on quantitative estimates of sea level rise. No probabilities were associated with these scenarios. Following the convention of a recent National Research Council report (Dean et al., 1987), the rise was interpolated throughout the 21st century using a quadratic (parabola). For each site, local subsidence was added to determine relative sea level rise. Figure 7-8 shows the scenarios for the coast of Florida where relative sea level rise will be typical of most of the U.S. coast. Sea level would rise 1 foot by 2025, 2040, and 2060 for the three scenarios and 2 feet by 2045, 2065, and 2100.

RESULTS OF SEA LEVEL STUDIES IN THIS REPORT

Loss of Coastal Wetlands and Dryland

Park (Volume B) sought to test a number of hypotheses presented in previous publications:

- A rise in sea level greater than the rate of vertical wetland accretion would result in a net loss of coastal wetlands.

- The loss of wetlands would be greatest if all developed areas were protected, less if shorelines retreated naturally, and least if barrier islands were protected while mainland shores retreated naturally.

- The loss of coastal wetlands would be greatest in the Southeast, particularly Louisiana.

Study Design

Park's study was based on a sample of 46 coastal sites that were selected at regular intervals. This guaranteed that particular regions would be represented in proportion to their total area in the coastal zone. The sites chosen accounted for 10% of the U.S. coastal zone excluding Alaska and Hawaii. To estimate the potential loss of wet and dry land, Park first had to characterize their elevations. For wetlands, he used satellite imagery to determine plant species for 60- by 80-meter parcels. Using estimates from the literature on the frequency of flooding that can be tolerated by various wetland plants, Park determined the percentage of time that particular parcels are currently under water.

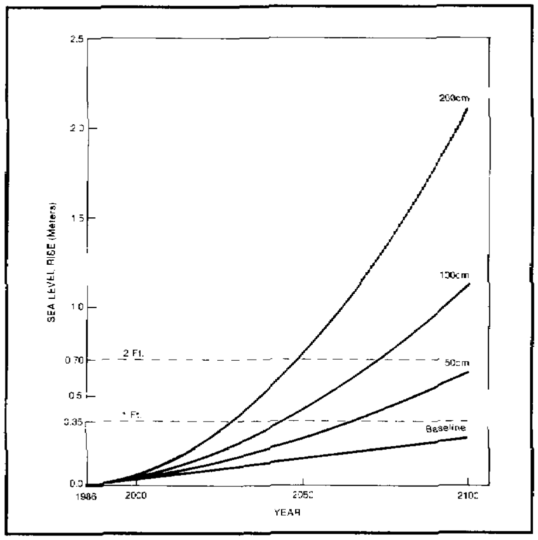


Figure 7-8. Sea level scenarios (Miami Beach).

From this, Park inferred wetland elevation based on the known tidal range. For dryland, he used spot elevation measurements to interpolate between contours on U.S. Geological Survey topographic maps.

Park estimated the net loss of wetlands and dryland for no protection, protection of developed areas, and protection of all shores. For the no-protection scenario, estimating the loss of dryland is straightforward. However, for calculating net wetland loss, Park had to estimate the loss of existing wetlands as well as the creation of new wetlands. For calculating losses, Park used published vertical accretion rates (see Armentano et al., 1988), although he allowed for some acceleration of vertical accretion in areas with ample supplies of sediment, such as tidal deltas. Park assumed that dryland would convert to wetlands within 5 years of being inundated.

For sites in the Southeast, Park also allowed for the gradual replacement of salt marshes by mangrove swamps. The upper limit for mangroves is around Fort Lauderdale. Park used the GISS transient scenario to determine the year particular sites would be as warm as Fort Lauderdale is today and assumed that mangroves would begin to replace marsh after that year.

Limitations

The greatest uncertainty in Park's analysis is a poor understanding of the potential rates of vertical accretion. Although this could substantially affect the results for low sea level rise scenarios, the practical significance is small for a rise of 1 meter because it is generally recognized that wetlands could not keep pace with the rise of 1 to 2 centimeters per year that such a scenario implies for the second half of the 21st century.

Errors can be made when determining vegetation type based on the use of infrared "signatures" that satellites receive. Park noted, for example, that in California the redwoods have a signature similar to that of marsh grass. For only a few sites, Park was able to corroborate his estimates of vegetation type.

Park's study did not consider the potential implications of alternative methods of managing riverflow. This limitation is particularly serious regarding application to Louisiana, where widely varying measures have been proposed to increase the amount of water and sediment delivered to the wetlands. Finally, the study makes no attempt to predict which undeveloped areas might be developed in the next century.

At the coarse (500-meter) scale Park used, the assumption of protecting only developed areas amounts to not protecting a number of mainland areas where the shoreline is developed but areas behind the shoreline are not. Therefore, Park's estimates for protecting developed areas should be interpreted as applying to the case where only densely developed areas are protected. Finally, Park's assumption that dryland would convert to vegetated wetlands within 5 years of being inundated probably led him to underestimate the net loss of wetlands due to sea level rise.

Results

Park's results supported the hypotheses suggested by previous studies. Figure 7-9 shows nationwide wetlands loss for various (0- to 3-meter) sea level rises for the three policy options investigated. For a 1-meter rise, 66% of all coastal wetlands would be lost if all shorelines were protected, 49% would be lost if only developed areas were protected, and 46% would be lost if shorelines retreated naturally.

As expected, the greatest losses of wetlands would be in the Southeast, which currently contains 85% of U.S. coastal wetlands (Figure 7-9). For a 1-meter sea level rise, 6,000 to 8,600 square miles (depending on which policy is implemented) of U.S. wetlands would be lost; 90 to 95% of this area would be in the Southeast, and 40 to 50% would be in Louisiana alone. By contrast, neither the Northeast nor the West would lose more than 10% of its wetlands if only currently developed areas are protected.

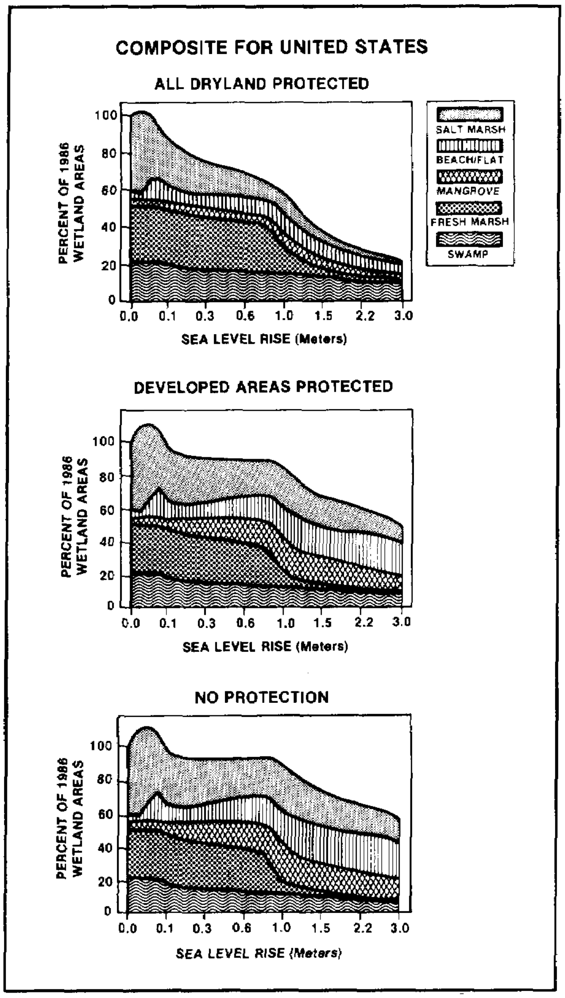


Figure 7-9. Nationwide wetlands loss for three shoreline-protection options. Note: These wetlands include beaches and flats that are not vegetated wetlands; however, results cited in the text refer to vegetated wetlands (Park, Volume B).

Figure 7-10 illustrates Park's estimates of the inundation of dryland for the seven coastal regions. If shorelines retreated naturally, a 1-meter rise would inundate 7,700 square miles of dryland, an area the size of Massachusetts. Rises of 50 and 200 centimeters would result in losses of 5,000 and 12,000 square miles, respectively. Approximately 70% of the dryland losses would occur in the Southeast, particularly Florida, Louisiana, and North Carolina. The eastern shores of the Chesapeake and Delaware Bays also would lose considerable acreage.

Costs of Defending Sheltered Shorelines

Study Design

This study began by examining Long Beach Island in depth. This site and five other sites were used to develop engineering rules of thumb for the cost of protecting coastal lowlands from inundation. Examining the costs of raising barrier islands required an assessment of two alternatives: (1) building a levee around the island; and (2) allowing the island to migrate landward.

After visiting Long Beach Island and the adjacent mainland, Weggel (Volume B) designed and estimated costs for an encirclement scheme consisting of a levee around the island and a drainage system that included pumping and underground retention of stormwater. For island migration, he used the Bruun Rule to estimate oceanside erosion and navigation charts to calculate the amount of sand necessary to fill the bay an equivalent distance landward. For island raising and island migration, Weggel used the literature to estimate the costs of elevating and moving houses and of rebuilding roads and utilities.

Weggel's approach for estimating the nationwide costs was to examine a number of index sites in depth and thereby develop generalized cost estimates for protecting different types of shorelines. He used the topographic information collected by Park for a sample of 95 sites to determine the area and shoreline length that had to be protected. He then applied the cost estimation factors to each site and extrapolated the sample to the entire coast.

After assessing Long Beach Island, Weggel conducted less detailed studies of the following areas:

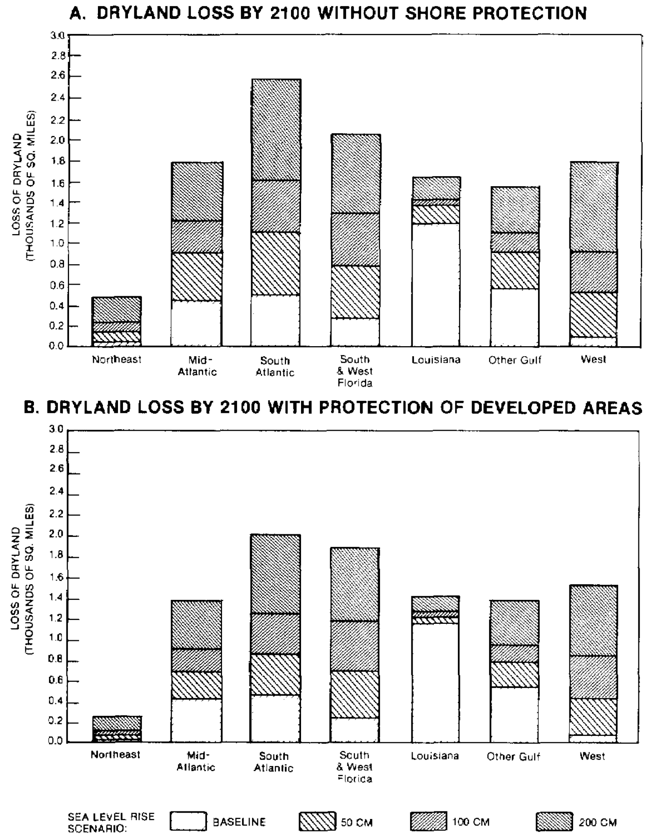


Figure 7-10. Loss of dryland by 2100: (A) if no areas are protected, and (B) if developed areas are protected with levees (derived from Park, Volume B; see also Titus and Greene, Volume B).

metropolitan New York; Dividing Creek, New Jersey; Miami and Miami Beach; the area around Corpus Christi, Texas; and parts of San Francisco Bay.

Limitations

The most serious limitation of the Weggel study is that cruder methods are used for the national assessment than for the index sites. Even for the index sites, the cost estimates are based on the literature, not on site-specific designs that take into consideration wave data for bulkheads and potential savings from tolerating substandard roads. Weggel did not estimate the cost of pumping rainwater out of areas protected by levees.

Finally, Weggel was able to examine only one scenario: a 2-meter rise by 2100. This scenario was chosen over the more likely 1-meter scenario because an interpolation from 2 meters to 1 meter would be more reliable than an extrapolation from 1 meter to 2 meters. (See the discussion of Titus and Greene for results of the interpolation.)

Results

Case Study of Long Beach Island

Weggel's cumulative cost estimates clearly indicate that raising Long Beach Island would be much less expensive ($1.7 billion) than allowing it to migrate landward ($7.7 billion). Although the cost of building a levee around the island ($800 million) would be less, the "present value" would be greater. Weggel concluded that the levee would have to be built in the 2020s, whereas the island could be raised gradually between 2020 and 2100. Thus, the (discounted) present value of the levee cost would be greater, and raising the necessary capital for a levee at any one time could be more difficult than gradually rebuilding the roads and elevating houses as the island was raised. Moreover, a levee would eliminate the waterfront view. A final disadvantage of building a levee is that one must design for a specific magnitude of sea level rise; by contrast, an island could be raised incrementally.

The Weggel analysis shows that landward migration is more expensive than island raising, primarily because of the increased costs of rebuilding infrastructure. Thus, migration might be less expensive in the case of a very lightly developed island. Levees might be more practical for wide barrier islands where most people do not have a waterfront view.

Nationwide Costs

Table 7-2 shows Weggel's estimates for the index sites and his nationwide estimate. The index sites represent two distinct patterns. Because urban areas such as New York and Miami would be entirely protected by levees, the cost of moving buildings and rebuilding roads and utilities would be relatively small. On the other hand, Weggel concluded that in more rural areas such as Dividing Creek, New Jersey, only the pockets of development would be protected. The roads that connected them would have to be elevated or replaced with bridges, and the small number of isolated buildings would have to be moved.

Weggel estimates that the nationwide cost of protecting developed shorelines would be $25 billion, assuming bulkheads are built, and $80 billion assuming levees are built. Unlike wetlands loss, the cost of protecting developed areas from the sea would be concentrated more in the Northeast than in the Southeast because a much greater portion of the southeastern coast is undeveloped.

Table 7-1. Total Cost of Protecting Long Beach Island from a 2-Meter Rise in Sea Level (millions of 1986 dollars)

Protective measure	Encirclement	Island raising	Island mitigation
Sand Costs			
Beach	290	290	0
Land creation/maintenance	NA	270	321
Moving/elevating houses	NA	74	37
Roads/utilities	0	1072	7352
Levee and drainage	542	0	0
Total	832	1706	7710

NA = Not applicable.
Source: Leatherman (Volume B); Weggel (Volume B)

Table 7-2. Cumulative Cost of Protecting Sheltered Waters for a 2-Meter Rise in Sea Level (millions of 1986 dollars)

	New bulkhead	Raise old bulkhead	Move building	Roads/ utilities	Total
Index sites					
New York	57	205	0.5	9.5	272.3
Long Beach Island	3	4	2.7	3.8	13.7
Dividing Creek	4	6	4.8	18.2	33.0
Miami area	11	111	0.3	8.3	130.7
Corpus Christi	11	29	2.8	40.9	83.4
San Francisco Bay[a]	3	19	2.0	20.0	44.0
Nationwide estimate					
	low		high		
Northeast	6,932		23,607		
Mid-Atlantic	4,354		14,603		
Southeast	9,249		29,883		
West	4,097		12.802		
Nation	24,633		80,176		

[a] Site names refer to the name of the U.S. Geological Survey quadrant, not to the geographical area of the same name.
Source: Weggel et al. (Volume B).

Case Study of the Value of Threatened Coastal Property

Study Design

Yohe's (Volume B) objective was to estimate the loss of property that would result from not holding back the sea. Using estimates of erosion and inundation for Long Beach Island from Leatherman and Park et al., Yohe determined which land would be lost from sea level rise for a sample of strips spanning the island from the ocean to the bay. He then used the Ocean County, New Jersey, tax assessor's estimates of the value of the land and structures that would be lost, assuming that the premium associated with a view of the bay or ocean would be transferred to another property owner and not lost to the community. He estimated the annual stream of rents that would be lost by assuming that the required return on real estate is 10% after tax. Yohe assumed that a property on the bay side was "lost" whenever it was flooded at high tide, and that property on the ocean side was "lost" when the house was within 40 feet of the spring high tide mark. (See Titus and Greene, Volume B, for discussion.)

Limitations

Yohe's results for a sea level rise of less than 18 inches are sensitive to the assumption regarding when a property would be lost. On the bay side, people might learn to tolerate tidal inundation. Unless a major storm occurred, people could probably occupy oceanfront houses until they were flooded at high tide. However, the resulting loss of recreational use of the beach probably would have a greater impact than abandoning the structure. Tax maps do not always provide up-to-date estimates of property values. However, the distinction between the tax assessor's most recent estimate of market value and the current market value is small compared with the possible changes in property values that will occur over the next century; hence, Titus and Greene used tax assessors estimates of market values.

Results

Yohe's results suggest that the cost of gradually raising Long Beach Island would be far less than the value of the resources that would be protected. Figure 7-6 compares Yohe's estimates of the annual loss in rents resulting from not holding back the sea with Weggel's estimates of the annual cost of raising the island for the 2-meter scenario. With the exception of the 2020s, the annual loss in rents resulting from not holding back the sea would be far less than the annual costs of pumping sand and elevating structures. Titus and Greene point out that the cost would be approximately $1,000 per year per house, equivalent to 1 week's rent (peak season).

Nationwide Cost of Pumping Sand Onto Recreational Beaches

Leatherman's goal (Volume B) was to estimate the cost of defending the U.S. ocean coast from a rise in sea level.

Study Design

Owing to time constraints, it was possible to consider only one technology. Based on the Long Beach Island results, Leatherman assumed that the cost of elevating recreational beaches and coastal barrier islands by pumping in offshore sand would provide a more representative cost estimate than assuming that barrier islands would be abandoned, would migrate landward, or would be encircled with dikes and levees.

The first step in Leatherman's analysis was to estimate the area of (1) the beach system, (2) the low bayside, and (3) the slightly elevated oceanside of the island. Given the areas, the volume of sand was estimated by assuming that the beach system would be raised by the amount of sea level rise. The bay and ocean sides of the island would not be raised until after a sea level rise of 1 and 3 feet, respectively. Cost estimates for the sand were derived from inventories conducted by the U.S. Army Corps of Engineers.

Leatherman applied this method to all recreational beaches from Delaware Bay to the mouth of the Rio Grande, as well as California, which accounts for 80% of the nation's beaches. He also examined one representative site in each of the remaining states.

Limitations

Although the samples of sites in the Northeast and Northwest are representative, complete coverage would have been more accurate. Furthermore, Leatherman used conservative assumptions in estimating the unit costs of sand. Generally, a fraction of the sand placed on a beach washes away because the sand's grain is too small. Moreover, as dredges have to move farther offshore to find sand, costs will increase.

For Florida, Leatherman used published estimates of the percentage of fine-grain sand and assumed that the dredging cost would rise $1 per cubic yard for every additional mile offshore the dredge had to move. For the other states, however, he assumed that the deposits mined would have no t-me-grain sand and that dredging costs would not increase. (To test the sensitivity of this assumption, Titus and Greene developed an increasing-cost scenario.) Leatherman assumed no storm worse than the 1-year storm, which underestimates the sand volumes required.

A final limitation of the Leatherman study is that it represents the cost of applying a single technology throughout the ocean coasts of the United States. Undoubtedly, some communities (particularly Galveston and other wide barrier islands in Texas) would find it less expensive to erect levees and seawalls or to accept a natural shoreline retreat.

Results

Table 7-3 illustrates Leatherman's estimates. A total of 1,900 miles of shoreline would be nourished. Of 746 square miles of coastal barrier islands that would be raised for a 4-foot sea level rise, 208 square miles would be for a 2-foot rise. As the table shows, two-thirds of the nationwide costs would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina.

Figure 7-11 illustrates the cumulative nationwide costs over time. For the 50- and 200-centimeter scenarios, the cumulative cost would be $2.3 to $4.4 billion through 2020, $11 to $20 billion through 2060, and $14 to $58 billion through 2100. By

Table 7-3. Cost of Placing Sand on U.S. Recreational Beaches and Coastal Barrier Islands and Spits (millions of 1986 dollars).

	Sea level rise by 2100			
State	Baseline	50 cm	100 cm	200 cm
Maine[a]	22.8	119.4	216.8	412.2
New Hampshire[a]	8.1	38.9	73.4	142.0
Massachusetts[a]	168.4	489.5	841.6	1,545.8
Rhode Island[a]	16.3	92.0	160.6	298.2
Connecticut[a]	101.7	516.4	944.1	1,799.5
New York[a]	143.6	769.6	1,373.6	2,581.4
New Jersey[a]	157.6	902.1	1,733.3	3,492.5
Delaware	4.8	33.6	71.1	161.8
Maryland	5.7	34.5	83.3	212.8
Virginia	30.4	200.8	386.5	798.0
North Carolina	137.4	655.7	1,271.2	3,240.4
South Carolina	183.5	1,157.9	2,147.7	4,347.7
Georgia	25.9	153.6	262.6	640.3
Florida (Atlantic coast)	120.1	786.6	1,791.0[b]	7,745.5[b]
Florida (Gulf coast)	149.4	904.3	1,688.4[b]	4,091.6[b]
Alabama	11.0	59.0	105.3	259.6
Mississippi	13.4	71.9	128.3	369.5
Louisiana	1,955.8	2,623.1	3,492.7	5,231.7
Texas	349.6	4,188.3	8,489.7	17,608.3
California	35.7	147.1	324.3	625.7
Oregon[a]	21.9	60.5	152.5	336.3
Washington State[a]	51.6	143.0	360.1	794.4
Hawaii[a]	73.5	337.6	646.9	1,267.5
Nation	3,788.0	14,512.0	26,745.0	58,002.0

[a] Indicates states where estimate was based on extrapolating a representative site to the entire state. All other states have 100% coverage.

[b] Florida estimates account for the percentage of fine-grain sediment, which generally washes away, and for cost escalation as least expensive sand deposits are exhausted. All other estimates conservatively ignore this issue.

Source: Leatherman (Volume B) (baseline derived from Leatherman).

contrast, if current trends continue, the total cost of sea level rise for beach nourishment would be about $35 million per year.

Synthesis of the Three National Studies

Study Design

Although Weggel used Park's topographic data, the analysis in the three nationwide studies proceeded independently. Titus and Greene's primary objectives (Volume B) were to combine various results to estimate the nationwide cost of holding back the sea for various sea level rise scenarios and to derive the ranges for the specific impacts. The objectives were as follows:

1. Use Park's results to weigh weggel's high and low scenarios according to whether levees or bulkheads would be necessary, and interpolate Weggel's cost estimate for the 2-meter rise to rises of 50 and 100 centimeters;
2. Use results from Leatherman and Weggel, along with census data, to estimate the nationwide cost (other than pumping sand) of raising barrier islands;
3. Develop an increasing-cost scenario for the cost of protecting the open ocean coast; and
4. Develop statistical confidence intervals for wetland loss, impacts of the various policy options, and costs of protecting developed shores.

Titus and Greene developed a single estimate for protecting each site with bulkheads and levees by assuming that the portion of developed areas protected with levees would be equal to the portion of the lowlands that Park estimated would be inundated. They interpolated the resulting 2-meter estimate to 50-and 100-centimeter estimates, based on Weggel's assumption that the cost of building bulkheads and levees rises as a function of the structure's height.

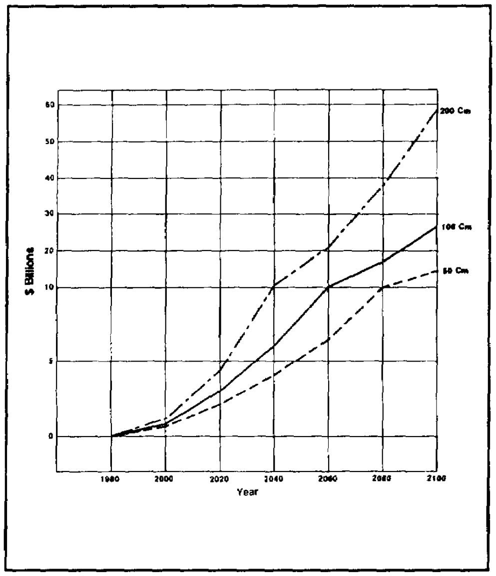


Figure 7-11. Nationwide cost of sand for protecting ocean coast (in 1986 dollars) (Leatherman, Volume B).

Cost of Protecting Sheltered Shores Cost of Raising Barrier Islands Other Than Dredging

Weggel's case study of Long Beach Island provided cost estimates for elevating structures and rebuilding roads, while Leatherman estimated the area that would have to be raised. Many barrier islands have development densities different from those of Long Beach Island because they have large tracts of undeveloped land or larger lot sizes. Therefore, Titus and Greene used census data to estimate a confidence interval for the average building density of barrier islands, and they applied Weggel's cost factors.

Sensitivity of Sand Costs to Increasing Scarcity of Sand

Titus and Greene used Leatherman's escalating cost assumptions for Florida to estimate sand pumping costs for the rest of the nation.

Confidence Intervals

The Park and Weggel studies involved sampling, but the researchers did not calculate statistical confidence intervals. Therefore, Titus and Greene developed 95% confidence intervals for the cost of protecting sheltered coasts, the area of wetlands loss for various scenarios.

Limitations

Besides all of the limitations that apply to the Park, Leatherman, and Weggel studies, a number of others apply to Titus and Greene.

Cost of Protecting Sheltered Shores

Titus and Greene assumed that the portion of the coast requiring levees (instead of bulkheads) would be equal to the portion of lowlands that otherwise would be inundated. This assumption tends to understate the need for levees. For example, a community that is 75% high ground often would still have very low land along all of its shoreline and hence would require a levee along 100% of the shore. But Titus and Greene assume that only 25% would be protected by levees.

Cost of Raising Banier Islands

The data provided by Weggel focused only on elevating roads, buildings, and bulkheads. Thus, Titus and Greene do not consider the cost of replacing sewers, water mains, or buried cables. On the other hand, Weggel's cost factors assume that rebuilt roads would be up to engineering standards; it is possible that communities would tolerate substandard roads. In addition, the census data Titus and Greene used were only available for incorporated communities, many of which are part barrier island and part mainland; thus, the data provide only a rough measure of typical road density.

Sensitivity of Sand Costs to Increased Scarcity of Sand

Finally, Titus and Greene made no attempt to determine how realistic their assumption was that sand costs would increase by the same pattern nationwide as they would in Florida.

Results

Loss of Wetlands and Dryland

Table 7-4 illustrates 95% confidence intervals for the nationwide losses of wetlands and dryland. If all shorelines were protected, a 1-meter rise would result in a loss of 50 to 82% of U.S. coastal wetlands, and a 2-meter rise would result in a loss of 66 to 90%. If only the densely developed areas were protected, the losses would be 29 to 69% and 61 to 80% for the 1- and 2-meter scenarios, respectively. Except for the Northeast, no protection results in only slightly lower wetland loss than protecting only densely developed areas. Although the estimates for the Northeast, midAtlantic, the gulf regions outside Louisiana, and the Florida peninsula are not statistically significant (at the 95% confidence levels), results suggest that wetlands loss would be least in the Northeast and Northwest.

Table 7-4. Nationwide Loss of Wetlands and Dryland[a] (95% confidence intervals)

	Square miles[b]			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Wetlands				
Total protection	N.C.	4944-8077 (38-61)	6503-10843 (50-82)	8653-11843 (66-90)
Standard protection	1168-3341 (9-25)	2591-5934 (20-45)	3813-9068 (29-69)	4350-10995 (33-80)
No protection	N.C.	2216-5592 (17-43)	3388-8703 (26-66)	3758-10025 (29-76)
Dryland				
Total protection	0	0	0	0
Standard protection	1906-3510	2180-6147	4136-9186	6438-13496
Total protection	N.C.	3315-7311	5123-10330	8791-15394

a Wetlands loss refers to vegetative wetlands only. b Numbers in parentheses are percentages N.C.= not calculated.
Source: Titus and Greene (Volume B).

Table 7-5. Cumulative Nationwide Cost of Protecting Barrier Islands and Developed Mainland Through the Year 2100 (billions of 1986 dollars)[a]

	Sea level scenario			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Open coast				
Sand	3.8	15-20	27-41	58-100
Raise houses, roads, utilities	0	9-13	21-57	75-115
Sheltered shores	1.0-2.4	5-13	11-33	30-101
Total[b]	4.8-6.2	32-43	73-111	119-309

[a] Costs due to sea level rise only

[b] Ranges for totals are basd in the square root of the sum of the squared ranges.

Source: Titus and Green (Volume B).

Costs of Holding Back the Sea

Table 7-5 illustrates the Titus and Greene estimates of the costs of holding back the sea. The low range for the sand costs is based on Leatherman's study, and the high range is based on the increasing cost scenario Titus and Greene developed. The uncertainty range for the costs of elevating structures reflects the uncertainty in census data regarding the current density of development. High and low estimates for the cost of protecting sheltered shorelines are based on the sampling errors of the estimates for the 46 sites that both Park et al. and Weggel et al. examined.

Titus and Greene estimated that the cumulative nationwide cost of protecting currently developed areas in the face of a 1-meter rise would be from $73 to 111 billion, with costs for the 50- and 200-centimeter scenarios ranging from $32 to 309 billion. These costs would imply a severalfold increase in annual expenditures for coastal defense. Nevertheless, compared with the value of coastal property, the costs are small.

POLICY IMPLICATIONS

Wetlands Protection

The nationwide analysis showed that a 50- to 200-centimeter rise in sea level could reduce the coastal wetlands acreage (outside Louisiana) by 17 to 76% if no mainland areas were protected, by 20 to 80% if only currently developed areas were protected, and by 38 to 90% if all mainland areas were protected. These estimates of the areal losses understate the differences in impacts for the various land-use options. Although a substantial loss would occur even with no protection, most of today's wetland shorelines would still have wetlands; the strip simply would be narrower. By contrast, protecting all mainland areas would generally replace natural shorelines with bulkheads and levees. This distinction is important because for many species of fish, the length of a wetland shoreline is more critical than the total area.

Options for State and Local Governments

Titus (1986) examined three approaches for maintaining wetland shorelines in the face of a rising sea: (1) no further development in lowlands; (2) no action now but a gradual abandonment of lowlands as sea level rises; and (3) allowing future development only with a binding agreement to allow such development to revert to nature if it is threatened by inundation.

The first option would encounter legal or financial hurdles. The extent to which the "due-process" clause of the Constitution would allow governments to prevent development in anticipation of sea level rise has not been specifically addressed by the courts. Although purchases of land would be feasible for parks and refuges, the cost of buying the majority of lowlands would be prohibitive. Moreover, this approach requires preparation for a rise in sea level of a given magnitude; if and when the sea rises beyond that point, the wetlands would be lost. Finally, preventing future development would not solve the loss of wetlands resulting from areas that have already been developed.

Enacting no policy today and addressing the issue as sea level rises would avoid the costs of planning for the wrong amount of sea level rise but would probably result in less wetlands protection. People are developing coastal property on the assumption that they can use the land indefinitely. It would be difficult for any level of government to tell property owners that they must abandon their land with only a few years' notice, and the cost of purchasing developed areas would be even greater than the cost of buying undeveloped areas.

Economic theory suggests that under the third alternative, people would develop a property only if the temporary use provided benefits greater than the costs of writing it off early. This approach would result in the greatest degree of flexibility, because it would allow real estate markets to incorporate sea level rise and to determine the most efficient use of land as long as it remains dry.

This approach could be implemented by regulations that prohibit construction of bulkheads as sea level rises or by the use of conditional longterm leases that expire when high tide falls above a property's elevation.

The State of Maine (1987) has implemented this third approach through its coastal dune regulations, which state that people building houses along the shore should assume that they will have to move their houses if their presence prevents the natural migration of coastal wetlands, dunes, or other natural shorelines. A number of states also have regulations that discourage bulkheads, although they do not specifically address sea level rise. The option can be implemented through cooperative arrangements between developers, conservancy groups, and local governments. (See Titus and Greene, Volume B, for additional details.)

The Federal Role

Section 404 of the Clean Water Act discourages development of existing wetlands, but it does not address development of areas that might one day be necessary for wetland migration. This program will provide lasting benefits, even if most coastal wetlands are inundated. Although marshes and swamps would be inundated, the shallow waters that formed could provide habitat for fish and submerged aquatic vegetation. No one has assessed the need for a federal program to protect wetlands in the face of rising sea level.

Coastal Protection

State and Local Efforts

State and local governments currently decide which areas would be protected and which would be allowed to erode. Currently, few localities contribute more than 10% of the cost of beach nourishment, with the states taking on an increasing share from the federal government. However, many coastal officials doubt that their states could raise the necessary funds if global warming increased the costs of coastal protection over the next century by $50 to $300 billion. If state funds could not be found, the communities themselves would have to take on the necessary expenditures or adapt to erosion.

Long Beach Island, New Jersey, illustrates the potential difficulties. The annual cost of raising the island would average $200 to $1,000 per house over the next century (Titus and Greene, Volume B). Although this amount is less than one week's rent during the summer, it would more than double property taxes, an action that is difficult for local governments to contemplate. Moreover, the island is divided into six jurisdictions, all of which would have to participate.

More lightly developed communities may decide that the benefits of holding back the sea are not worthwhile. Sand costs would be much less for an island that migrated. Although Weggel estimated that higher costs would be associated with allowing Long Beach Island to migrate landward than with raising the island in place, this conclusion resulted largely from the cost of rebuilding sewers and other utilities that would still be useful if the island were raised.

Regardless of how a barrier island community intends to respond to sea level rise, the eventual costs can be reduced by deciding on a response well in advance. The cost of raising an island can be reduced if roads and utilities are routinely elevated or if they have to be rebuilt for other reasons (e.g., Titus et al., 1987). The cost of a landward migration also can be reduced by discouraging reconstruction of oceanfront houses destroyed by storms (Titus et al., 1984a). The ability to fund the required measures also would be increased by fostering the necessary public debate well before the funds are needed.

Federal Efforts

While state governments generally are responsible for protecting recreational beaches, the U.S. Army Corps of Engineers is responsible for several major federal projects to rebuild beaches and for efforts to curtail land loss in Louisiana. The long-term success of these efforts would be improved if the corps were authorized to develop comprehensive long-term plans to address the impacts of sea level rise.

Beach Erosion

In its erosion-control efforts, the corps has recently shifted its focus from hard structures (e.g., seawalls, bulkheads, and groins) to soft approaches, such as pumping sand onto beaches. This shift is consistent with the implications of sea level rise: groins and seawalls will not prevent loss of beaches due to sea level rise. Although more sand will have to be pumped than current analyses suggest, this approach could ensure the survival of the nation's beaches.

Nevertheless, consideration of accelerated sea level rise would change the cost-benefit ratios of many corps erosion control projects. As with the operations of reservoirs (discussed in Chapter 16: Southeast), the corps is authorized to consider flood protection but not recreation. When they evaluated the benefits of erosion control at Ocean City, Maryland, the corps concluded that less than 10% of the benefits would be for flood control (most were related to recreation). Had they considered accelerated sea level rise, however, the estimated flood protection benefits from having a protective beach would have constituted a considerably higher fraction of the total benefits (Titus, 1985).

Wetlands Loss in Louisiana

By preventing freshwater and sediment from reaching the coastal wetlands, federal management of the Mississippi River is increasing the vulnerability of coastal Louisiana to a sea level rise (e.g., Houck, 1983). For example, current navigation routes require the U.S. Army Corps of Engineers to limit the amount of water flowing through the Atchafalaya River and to close natural breaches in the main channel of the Mississippi; these actions limit the amount of freshwater and sediment reaching the wetlands. Alternative routes have been proposed that would enable water and sediment to reach the wetlands (Louisiana Wetland Protection Panel, 1987). These include dredging additional canals parallel to the existing Mississippi River gulf outlet or constructing a deepwater port east of the city.

Either of these options would cost a few billion dollars. By contrast, annual resources for correcting land loss in Louisiana have been in the tens of millions of dollars. As a result, mitigation activities have focused on freshwater diversion structures and on other strategies that can reduce current wetland loss attributable to high salinities but that would not substantially reduce wetlands loss if sea level rises 50 to 200 centimeters (Louisiana Wetland Protection Panel, 1987).

The prospect of even a 50-centimeter rise in sea level suggests that solving the Louisiana wetlands loss problem is much more urgent than is commonly assumed. Because federal activities are now a major cause of land loss, and would have to be modified to enable wetlands to survive a rising sea, the problem is unlikely to be solved without a congressional mandate. A recent interagency report concluded that "no one has systematically determined what must be done to save 10, 25, or 50 percent of Louisiana's coastal ecosystem" (Louisiana Wetland Protection Panel, 1987). Until someone estimates the costs and likely results of strategies with a chance of protecting a significant fraction of the wetlands in face of rising sea level, it will be difficult for Congress to devise a long-term solution.

Flood Insurance

In 1968, Congress created the National Flood Insurance Program with the objective of reducing federal disaster relief resulting from floods. The Federal Emergency Management Agency (FEMA), which already had responsibility for administering disaster relief, was placed in charge of this program as well.

The National Flood Insurance Program sought to offer localities an incentive to prevent flood-prone construction. In return for requiring that any construction in a floodplain be designed to withstand a 100-year flood, the federal government would provide subsidized insurance to existing homes and a fair-market rate for any new construction (which was itself a benefit, since private insurers generally did not offer flood insurance). Moreover, as long as a community joined the program, it would continue to be eligible for federal disaster relief; if it did not join, it would no longer be eligible. As a result of this program, new coastal houses are generally elevated on pilings.

Although Congress intended to prevent coastal disasters, the National Flood Insurance Act does not require strategic assessments of long-term issues (see Riebsame, Volume J). Thus, FEMA has not conducted strategic assessments of how the program could be managed to minimize flood damage from shoreline retreat caused by both present and future rates of sea level rise.

Congress recently enacted the Upton-Jones Amendment (Public Housing Act of 1988), which commits the federal government to pay for rebuilding or relocating houses that are about to erode into the sea. Although the cost of this provision is modest today, a sea level rise could commit the federal government to purchase the houses on all barrier islands that did not choose to hold back the sea. Furthermore, this commitment could increase the number of communities that decided not to hold back the sea.

The planned implementation of actuarially sound insurance rates would ensure that as sea level rise increased property risk, insurance rates would rise to reflect the risk. This would discourage construction of vulnerable houses, unless their value was great enough to outweigh the likely damages from floods. However, statutes limiting the rate at which flood insurance rates can increase could keep rates from rising as rapidly as the risk of flooding, thereby increasing the federal subsidy.

No assessment of the impacts of sea level rise on the federal flood insurance program has been undertaken.

Sewers and Drains

Sea level rise also would have important impacts on coastal sewage and drainage systems. Wilcoxen (1986) examined the implications of the failure to consider accelerated sea level rise in the design of San Francisco's West Side (sewerage) Transport, which is a large, steel-reinforced concrete box buried under the city's ocean beach. He found that beach erosion will gradually expose the transport to the ocean, leaving the system vulnerable to undermining and eventual collapse. Protection costs for the $100 million project would likely amount to an additional $70 million. Wilcoxen concludes that had sea level rise been considered, the project probably would have been sited elsewhere.

The impacts of sea level rise on the construction grants program probably would be less in most other cases. As sea level rises, larger pumps will be necessary to transport effluents from settling ponds to the adjacent body of water. However, sea level rise would not necessarily require alternative siting. The projects serving barrier islands often are located on the mainland, and projects located on barrier islands are generally elevated well above flood levels. If barrier islands are raised in response to sea level as the nationwide analysis suggests, sewerage treatment plants will be a small part of the infrastructure that has to be modified.

Engineering assessments have concluded that it is already cost-beneficial to consider sea level rise in the construction of coastal drainage systems in urban areas. For example, the extra cost of installing the larger pipes necessary to accommodate a 1-foot rise in sea level would add less than 10% to the cost of rebuilding a drainage system in Charleston, South Carolina; however, failure to consider sea level rise would require premature rebuilding of the $4 million system (Titus et al., 1987).

RESEARCH NEEDS

A much better understanding of erosion processes is needed to (1) understand how much erosion will take place if no action is taken; and (2) help identify the most cost-effective means for protecting sandy shores. An improved understanding of how wetland accretion responds to different temperatures, higher CO_2 concentrations, changing mineral content, and the drowning of adjacent wetlands is needed. This will refine our ability to project future wetlands loss and, perhaps, devise measures for artificially enhancing their vertical growth.

This report did not examine the impacts of increased flooding because flood models have not been applied to the large numbers of coastal sites that would be necessary to conduct a nationwide assessment. Time-dependent estuarine salinity models, such as that of the Delaware River Basin Commission, should be applied to major estuaries to examine impacts on ecosystems and drinking water supplies.

Assessments of the impacts of global warming on coastal environments would be greatly improved by better estimates of future sea level rise. In addition to the improved ocean modeling that will be necessary for better projections of surface air temperatures (see Chapter 2: Climate Change), this will also require a substantial increase in the resources allocated for monitoring and modeling glacial processes. Finally, this report assumed that winds, waves, and storms remained constant; future studies will need estimates of the changes in these climatic variables.

REFERENCES

Armentano, T.V., R.A. Park, and C.L. Cloonan. 1988. Impacts on coastal wetlands throughout the United States. In: Titus, J.G. ed. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Barnett, T.P. 1984. The estimation of "global" sea level change: a problem of uniqueness. Journal of Geophysical Research 89(CS):7980-7988.

Barth, M.C., and J.G. Titus, eds. 1984. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Bentley, C.R. 1983. West Antarctic ice sheets: diagnosis and prognosis. In: Proceedings of the Carbon Dioxide Research Conference: Carbon Dioxide, Science, and Consensus. Conference 820970. Washington, DC: Department of Energy.

Bruun, P. 1962. Sea level rise as a cause of shore erosion. Journal of Waterways and Harbors Division (ASCE) 1:116-130.

Dean, R.G. et al. 1987. Responding to Changes in Sea Level. Washington, DC: National Academy Press.

Dony, W.L., W.R. Farrand, and M. Ewing. 1962. Pleistocene ice volumes and sea level lowering. Journal of Geology 70:206-214.

Everts, C.H. 1985. Effect of sea level rise and net sand volume change on shoreline position at Ocean City, Maryland. In: Titus, J.G., ed. Potential Impact of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, DC: U.S. Environmental Protection Agency.

Fairbridge, R.W., and W.S. Krebs, Jr. 1962. Sea level and the southern oscillation. Geophysical Journal 6:532-545.

Gibbs, M. 1984. Economic analysis of sea level rise: methods and results. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Gornitz, V.S., S. Lebedeff, and J. Hansen. 1982. Global sea level trend in the past century. Science 215:1611-1614.

Hoffman, J.S., D. Keyes, and J.G. Titus. 1983. Projecting Future Sea Level Rise. Washington, DC: U.S. Environmental Protection Agency.

Hoffman, J.S., J. Wells, and J.G. Titus. 1986. Future global warming and sea level rise. In: Sigbjarnarson, G., ed. Iceland Coastal and River Symposium. Reykjavik, Iceland: National Energy Authority.

Houck, O.A. 1983. Land loss in coastal Louisiana: causes, consequences, and remedies. Tulane Law Review 58(1):3-168.

Howard, J.D., O.H. Pilkey, and A. Kaufman. 1985. Strategy for beach preservation proposed. Geotimes 30(12):15-19.

Hughes, T. 1983. The stability of the West Antarctic ice sheet: what has happened and what will happen. In: Proceedings of the Carbon Dioxide Research Conference: Carbon Dioxide, Science, and Consensus. Conference 820970. Washington, DC: Department of Energy.

Hull, C.H.J., and J.G. Titus. 1986. Responses to salinity increases. In: Hull, C.H.J., and J.G. Titus. 1986. Greenhouse Effect, Sea Level Rise, and Salinity in the Delaware Estuary. Washington, DC: U.S. Environmental Protection Agency and Delaware River Basin Commission.

Hull, C.H.J., and J.G. Titus. 1986. Greenhouse Effect, Sea Level Rise, and Salinity in the Delaware Estuary. Washington, DC: U.S. Environmental Protection Agency and Delaware River Basin Commission.

Kana, T.W., J. Michel, M.O. Hayes, and J.R. Jensen. 1984. The physical impact of sea level rise in the area of Charleston, South Carolina. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Kennett, J. 1982. Marine Geology. Englewood Cliffs, NJ: Prentice-Hall.

Kyper, T., and R. Sorenson. 1985. Potential impacts of sea level rise on the beach and coastal structures at Sea Bright, New Jersey. In: O.T. Magson, ed. Coastal Zone '85. New York: American Society of Civil Engineers.

Leatherman, S.P. 1984. Coastal geomorphic responses to sea level rise: Galveston Bay, Texas. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Louisiana Wetland Protection Panel. 1987. Saving Louisiana's Coastal Wetlands and the Need for a Long-Term Plan of Action. Washington, DC: U.S. Environmental Protection Agency/Louisiana Geological Survey. EPA-230-02-87-026.

Lyle, S.D., L.E. Hickman, and HA. Debaugh. 1987. Sea Level Variations in the United States. Rockville, MD: National Ocean Service.

Meier, M.F. et al. 1985. Glaciers, Ice Sheets, and Sea Level. Washington, DC: National Academy Press.

Meier, M.F. 1984. Contribution of small glaciers to global sea level. Science 226(4681):1418-1421.

Mercer, J.H. 1968. Antarctic ice and Sangamon sea level. Geological Society of America Bulletin 79:471.

Oldale, R. 1985. Late quaternary sea level history of New England: a review of published sea level data. Northeastern Geology 7:192-200.

Revelle, R. 1983. Probable future changes in sea level resulting from increased atmospheric carbon dioxide. In: Changing Climate. Washington, DC: National Academy Press.

Schelling, T. 1983. Climatic change: implications for welfare and policy. In: Changing Climate. Washington, DC: National Academy Press.

Sorensen, R.M., R.N. Weisman, and G.P. Lennon. 1984. Control of erosion, inundation, and salinity intrusion. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

State of Maine. 1987. Dune Rule 355. Augusta, ME: Maine Department of Environmental Protection.

Thomas, R.H. 1986. Future sea level rise and its early detection by satelite remote sensing. In: Titus, J.G., ed. Effects of Changes in Stratosphere Ozone and Global Climate. Washington, DC: U.S. EPA and United Nations Environment Programme.

Thomas, R.H. 1985. Responses of the polar ice sheets to climatic warming. In: Meier, M.F., D.G. Aubrey, C.R. Bentley, W.S. Broecker, J.E. Hansen, W.R. Peltier, and R.J.C. Somerville, eds. Glaciers, Ice Sheets, and Sea Level. Washington, DC: National Academy Press.

Titus, J.G. 1988. Sea level rise and wetlands loss: an overview. In: Titus, J.G., ed. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G., ed. 1988. Greenhouse Effect, Sea Level

Rise, and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G. 1987. The greenhouse effects, rising sea level, and society's response. In: Devoy, RJ.N. Sea Surface Studies. New York: Croom Heim.

Titus, J.G. 1986. Greenhouse effect, sea level rise, and coastal zone management. Coastal Zone Management Journal 14(3):147-171.

Titus, J.G. 1985. Sea level rise and the Maryland coast. In: Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G. 1984a. Planning for sea level rise before and after a coastal disaster. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Titus, J.G., M.C. Barth, J.S. Hoffman, M. Gibbs, and M. Kenney. 1984b. An overview of the causes and effects of sea level rise. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Titus, J.G., T. Henderson, and J.M. Teal. 1984. Sea level rise and wetlands loss in the United States. National Wetlands Newsletter 6:4.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Webb, and J.O. Waddell. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. Journal of Water Resources Planning and Management. American Society of Civil Engineers 113(2):216-227.

Wilcoxen, PJ. 1986. Coastal erosion and sea level rise: implications for ocean beach and San Francisco's West Side Transport Project. Coastal Zone Management Journal 14:3.

WMO. 1986. World Meteorological Organization. Atmospheric ozone 1985. Assessment of our understanding of the processes controlling its present distribution and change. Global Ozone Research and Monitoring Project, Report No. 16. Geneva, Switzerland: World Meteorological Organization.

CHAPTER 8
BIOLOGICAL DIVERSITY

FINDINGS

Unlike most other impacts, loss of species and reduced biological diversity are irreversible. The ability of a natural community to adapt to changing climate conditions will depend on the rate of climate change, the size of species ranges, the dispersal rates of the individual species, and whether or not barriers to species migration are present. If climate changes rapidly, many species will be lost.

Species Diversity

- The effect of climate change on species and ecosystems will most likely vary, with some species benefiting and others facing extinction. The uncertainties surrounding the rate of warming, individual species response, and interspecies dynamics make impacts difficult to assess. However, climate change would alter competitive outcomes and destabilize natural ecosystems in unpredictable ways.

- In many cases, the indirect effects of climate change on a population, such as changes in habitat, in food availability, and in predator/prey relationships, may have a greater impact than the direct physiological effects of climate change.

- Natural and manmade barriers, including roads, cities, mountains, bodies of water, agricultural land, unsuitable soil types, and habitat fragmentation, may block migration of species in response to climate change and exacerbate losses.

- The areas within the United States that appear to be most sensitive to changes in climate are those that have a number of threatened and endangered species, species especially sensitive to heat or drought stress, and species inhabiting coastal areas.

- Rapid climate change would add to the already existing threats biodiversity, faces from anthropogenic activities, such as deforestation and habitat fragmentation.

Marine Ecosystems

- The loss of coastal wetlands and coastal habitat resulting from sea level rise and saltwater intrusion may profoundly affect the populations of all inhabitants of these ecosystems, including mollusks, shellfish, finfish, and waterfowl. However, there is no evidence to indicate these species would become extinct.

Freshwater Ecosystems

- Freshwater fish in large bodies of water, such as the Great Lakes, may increase in productivity, but some significant species could decline. Fish in smaller bodies of water may be more constrained in their ability to respond to climate change. They also may be harmed by reductions in water quality.

Migratory Birds

- Migratory birds are likely to experience mixed effects from climate change, with some arctic nesting herbivores benefiting and continental nesters and shorebirds suffering. The loss of wintering grounds due to sea level rise and changing climate could harm many species, as would the loss of inland prairie potholes due to potentially increased continental dryness.

Policy Implications

- Existing refuges, sited to protect a species or ecosystem under current climate, may not be properly located for this purpose if climate changes or as species migrate.

- Wildlife agencies such as the Department of the Interior, state government agencies, and conservation organizations may wish to assess the feasibility of establishing migratory corridors to facilitate species migration.

- Areas that may become suitable future habitat for threatened and endangered species, such as lowland areas adjacent to current wetlands, need to be identified and protected.

- The practice of restoration ecology may need to be broadened to rebuild parts of ecosystems in new areas as climates shift.

- The increase in the number of species at risk as a result of climate change may require new strategies for balancing ecosystem level concerns with single species concerns. Agency programs such as the Fish and Wildlife Service's Endangered Species Program, may wish to assess the relative risk of climate change and more current stresses on ecological systems.

VALUE OF BIOLOGICAL DIVERSITY

Maintaining the biological diversity of our natural resources is an important goal for the nation. The preamble to the Endangered Species Act of 1973 emphasizes the value of individual species, stating that endangered and threatened species of fish, wildlife, and plants "are of aesthetic, ecological, educational, historical, recreational and scientific value to the Nation and its people." We depend upon our nation's biological resources for food, medicine, energy, shelter, and other important products. In addition to species diversity, the genetic variability within a species and the wide variety of ecosystems add to biological diversity. Reduced biological diversity could have serious implications for mankind as untapped resources for research in agriculture, medicine, and industry are irretrievably lost.

The evolving biological diversity of this planet is inevitably affected by climate change. Historic climate changes have resulted in major changes in species diversity. This has been true for the millions of years life has existed on Earth. Now our planet may face a more rapid change in climate that may have important consequences for biological diversity.

The National Resource

Public and private lands in the United States provide sanctuary for an abundant diversity of plants and animals. About 650 species of birds reside in or pass through the United States annually. Over 400 species of mammals, 460 reptiles, 660 freshwater fishes, and tens of thousands of invertebrates can be found in this country, in addition to some 22,000 plants (U.S. Fish and Wildlife Service, 1981). These species compose a wide variety of ecosystem types within the United States, including coniferous and broad-leaf forest, grassland, desert, freshwater, marine, estuarine, inland wetland, and agricultural ecosystems. Figure 8-1 shows the major ranges of natural vegetation in the United States.

The U.S. national parks, forests, wilderness areas, and fish and wildlife refuges are among the public lands that provide sanctuary for wildlife resources, including many endangered species. U.S. public lands, which encompass over 700 million acres (about 32% of the land area of the United States), support about 700 rare species and communities (Roush, 1986). Over 45% of the lands held by the Forest Service, Fish and Wildlife Service, National Park Service, and Bureau of Land Management are in Alaska, and over 48% are located in the 11 most western states (U.S. Department of the Interior, 1987). However, much of the nation's biological diversity lies outside these areas.

Private land holdings also account for a great deal of this nation's biological endowment. Private groups, such as the Nature Conservancy and the Audubon Society, manage 500,000 acres and 86,000 acres, respectively, for biological diversity.

GENERAL COMPONENTS OF BIOLOGICAL DIVERSITY

Biological diversity can be broadly defined as the full range of variety and variability within and among living organisms. It includes species diversity, genetic diversity, and ecosystemic or community

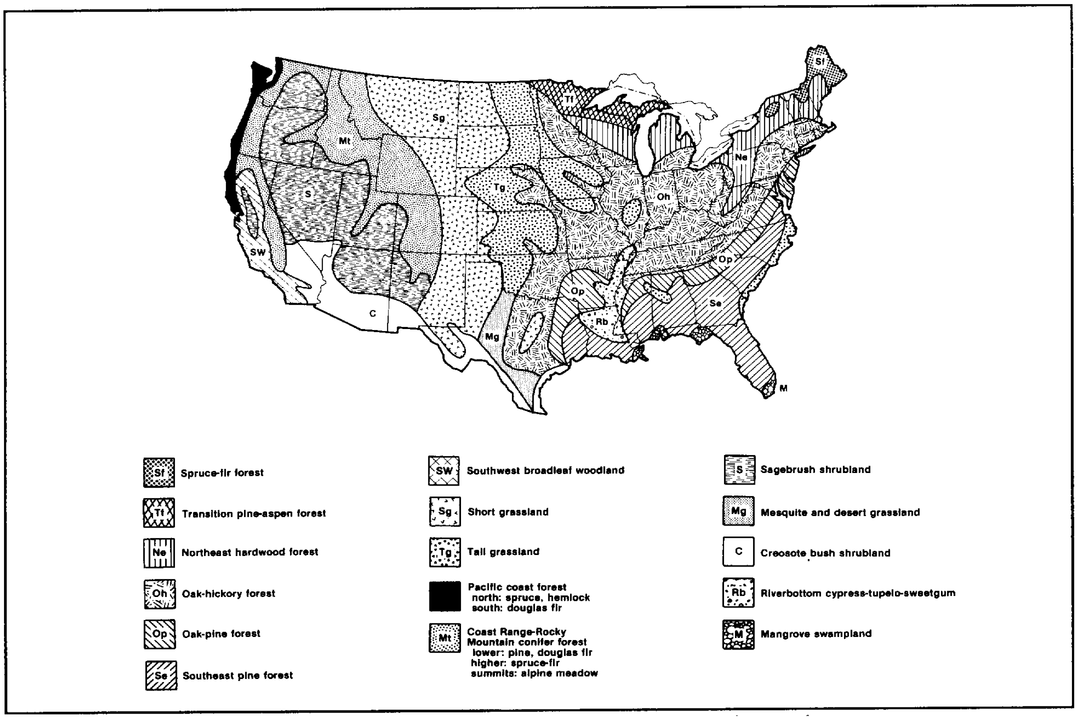


Figure 8-1. Natural vegetation in the United States (Hunt, 1972).

diversity. This report concentrates on species diversity, but only because it is better understood. Genetic and ecosystemic diversity are equally important.

Species Diversity

Each species occurs in a characteristic range or geographical area. The factors controlling species ranges are critical constraints on biological diversity. The presence of a species in an area suggests that the species must have successfully achieved the following: (1) dispersal into an area (no barriers to dispersal, such as the presense of bodies of water or unsuitable soil types); (2) survival in that area (the physical characteristics of the area were suited to the species' physiology, and food was available); and (3) establishment in the area (the organism found an appropriate place in the food web in the absence of excessive competition and predation, and was able to reproduce).

The stresses brought about by development, overuse, and alteration of habitat have fragmented much of the world's natural habitat and have created many new barriers. Consequently, for many species, dispersal has become much more difficult than it was in the past. For other species, humans have inadvertently aided dispersal and have caused rapid spread in recent years. Such practices as clearcut logging prevent the dispersal of species adapted to dense forest conditions (e.g., flying squirrels) and promote the dispersal of species suited to open areas (e.g., deer).

Currently, 495 species are listed as endangered within the United States, and over 2,500 species await consideration for that status by the Fish and Wildlife Service. The list of endangered species is dominated by plants, birds, fishes, and mammals but also includes insects, amphibians, reptiles, mollusks, and crustaceans (U.S. Fish and Wildlife Service, 1988).

New species are created through the evolutionary process of speciation, whereas existing species are lost through extinction. Speciation generally requires at least hundreds of thousands of years. However, extinction as a result of human activities, even without climate change, is occurring rapidly and at an increasing rate. Owing to its slowness, the process of speciation does little to offset species' loss to extinction.

Stressed Biological Diversity

Biological diversity continues to erode steadily around the globe as a result of human activities. Habitat destruction, degradation, and fragmentation have resulted in the loss of many species and have reduced the ranges and populations of others. These impacts affect all three levels of biological diversity. Through providing an additional pressure on ecological systems, climate change will further reduce the biological diversity in this nation and around the globe.

It is difficult to determine the exact rate of species extinction because the number of species on the Earth is known only to an order of magnitude. A recent estimate by Wilson (1988) places the total number of species between 5 and 30 million. Assuming 10 million species, Wilson made the rough calculation that one in every 1,000 species is lost each year. Wilson then compared this to estimates of extinction rates over geologic time, which ranged between 1 in every 1 million and 1 in every 10 million each year. Thus, human activities may be eliminating species at least 1,000 times faster than natural forces.

The significance of rare species should not be underestimated. A narrowly or sparsely distributed species may be a keystone in an ecosystem, controlling the structure and functioning of the community, or it may be a species of great and yet unknown value to humans.

Genetic Diversity

Each species that persists has a characteristic genetic diversity. The pool of genetic diversity within a species constitutes an adaptation to its present environment as well as a store of adaptive options for some possible changes in the environment. The loss of genetic diversity can contribute to the extinction of a species by reducing its ability to adapt to changing environmental conditions.

Generally, species with larger populations have greater genetic diversity. Species near extinction represented by few individuals in few populations have lower genetic diversity, a situation exacerbated by inbreeding. Additionally, extreme climatic events may cause bouts of natural selection that reduce genetic variability (Mayr, 1963).

Community and Ecosystemic Diversity

Ecosystemic diversity is the number of distinctive assemblages of species and biotic processes that occur in different physical settings. A long-leaf pine forest, a sand dune, and a small pond are all part of our diversity at this level. Ecosystems come into existence through complex physical and biological processes not now well understood. They may be lost by outright replacement of one by another (as in the desertification of a grassland) or by the gradual merging of two formerly separate ecosystems (as in the loss of some estuarine systems when they become saltier and take on more of the characteristics of a purely saltwater ecosystem). Ecosystems can also be eliminated because of human activities (as in the filling in of a wetland).

FACTORS AFFECTING THE RESPONSE OF BIOLOGICAL DIVERSITY TO CLIMATE CHANGE

Species respond to environmental change on a hierarchy of time scales. For relatively small changes occurring within the lifetime of an individual, each member of the species can respond through a variety of physiological adjustments. Individual species differ in their ability to adjust to change. Some can withstand a great deal of climate change, whereas others are restricted to a narrow range. Over several generations, natural selection can cause genetic adaptation and evolution in response to the change. Alternatively, a species can respond to climate change by moving into a new area through migration and dispersal. This can occur over a relatively short period of time if the species has the biological ability to move quickly. The discussion of response to climate change centers on migration as the response that could occur over a relatively short period of time.

The distributions of species are significant indicators of climate change. Local climate appears to be the primary factor defining an environmental setting and determining the species composition and spatial patterns of communities in terrestrial zones (Bolin et al., 1986). Temperature means, temperature extremes, and precipitation are the factors most often affecting the potential natural distributional limits of a species (Ford, 1982), while the actual distribution of a species is also affected by soil type, soil moisture, ecological dynamics, and regional isolation.

Rate of Climate Change

Predicting how a species or ecosystem might respond to a given environmental change is difficult. Adaptation to climate change will inextricably depend on the rate of climate change. For some species, migration rates may be inadequate to keep up.

The large number of combinations of dispersal range and age to reproduction make the potential rate of migration different for every species. Paleorecords suggest migration rates between 10 and 20 kilometers per century for chestnut, maple, and balsam fir, and between 30 and 40 kilometers per century for some oak and pine species (see Chapter 5: Forests). On the other hand, cattle egrets have shown a much quicker migration rate by colonizing all of the North American tropics within approximately 40 years.

As species shift at different rates in response to climate change, communities may disassociate into new arrangements of species. Local extinction can result either directly from physiological pressures or indirectly from changes in inter species dynamics. Hence, the effect of climate change on an area will be to cause sorting and separation of species as a result of the differential rate of migration and species retreat (Ford, 1982). Ecosystems, therefore, will not migrate as a unit.

Species do not immediately respond to changed and changing environmental conditions. A negative response, such as local extinction in an area, is usually quicker than the positive response of new species' colonization of a region (see Chapter 5: Forests). In the Arctics, the lag period between climate change and species response by migration and colonization may be several hundred years (Edlund, 1986). This lag period will leave areas open for weedy, opportunistic species that can quickly migrate and propagate in a region.

The rate of climate change will be crucial to the survival of the species in an ecosystem. A 3°C (5°F) increase in temperature, for example, would effect a several hundred kilometer poleward sluft in the temperate vegetation belts (Frye, 1983). If this change took place within a century, species would need to migrate several kilometers each year to adapt to this warming. Plants have a wide range of migration rates, and only some may be able to achieve this rate. Failure of a species to "keep up" with suitable environmental conditions would eventually result in extinction.

Many factors make evaluating the impact of climate change on ecosystems difficult. The great interdependencies among species in an ecosystem add considerable uncertainty to the effect that the various responses of individual species will have on the system. An impact upon a single species could profoundly affect the entire ecosystem. Certain species are vital to the workings of their ecosystems. Among them are large carnivores that regulate predator-prey relationships, large herbivores that significantly change vegetation, and organisms that pollinate plants (WRI, 1988). Plants can also be key species within an ecosystem. For example, elimination of a tree species in a region could have a significant effect on the whole forest ecosystem, including birds, insects, and mammals.

Animal populations are generally much more mobile than plants. But animal distributions heavily depend on vegetation for food, protection, and nesting habitat. Species not directly dependent on vegetation ultimately depend on some other species that is. The ranges of the fig wasp and the fig depend entirely upon one another. In this case, the plant species depends on a single pollinator, and the insect species relies upon a single species of plant for food (Kiester et al., 1984).

Effect on Genetic Diversity

With regard to genetic diversity, rapid climate change would select for those genotypes (combinations of genes) that were best suited to the new climate regime and would tend to eliminate others. This process of natural selection would usually decrease the genetic variability within a population. In the long term (evolutionary time), it is possible that greater climatic variability could select for greater genetic variability.

Barriers to Response

The rate of species migration is also affected by natural and manmade barriers and by competition. Peters and Darling (1985) examined the potential responses of species to climate change, ecological interactions, and barriers to adaptation. Physical barriers include mountains, bodies of water, roads, cities, agricultural land, inappropriate soil type, and habitat heterogeneity (landscape patchiness). A species whose migration rate is sufficient to keep up with changing conditions could become constrained by a physical barrier. Inability to cross the barrier could result in a reduction of the range of the species and its eventual extinction.

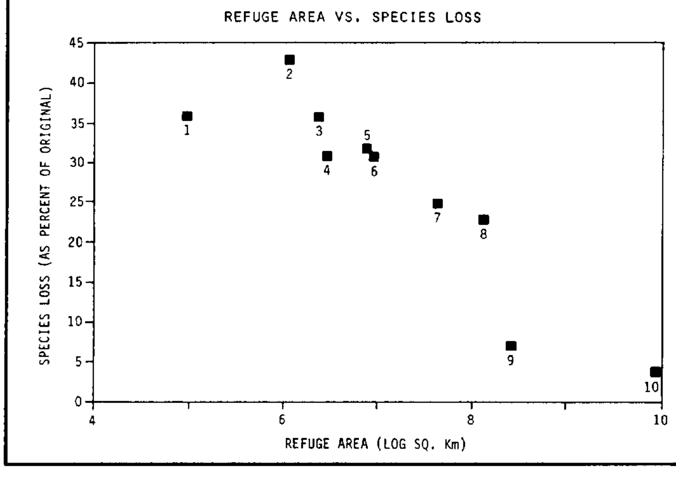
Reserve and Island Species

Additional constraints on the ability of populations living on reserves to respond to climate change frequently result from insufficient habitat area or isolation from other populations. The problem of isolation is similar to that of island species and has become known as the island dilemma. Species on reserves are often remnants of larger populations and are more susceptible to environmental stress and extinction.

Species on reserves are likely to be pressured from two directions as a result of climate change. A population isolated on a reserve surrounded by altered or unsuitable habitat receives little immigration from populations outside the reserve. Also, that population may not be able to colonize areas outside the reserve as these areas become suitable because of development or other alterations of habitat.

Even without the added pressure of climate change, reserve populations are vulnerable because many reserves are not large enough to support a self-sustaining population (Lovejoy, 1979). The predictive theory of island biogeography showed that, other factors being equal, small islands accommodate smaller numbers of species than do large islands (MacArthur and Wilson, 1967). This held true for other ecological "islands," such as mountaintops, woodlots, and lakes. Also, when large ecosystems become smaller through fragmentation, the number of species always declines. Figure 8-2 shows how mammalian extinctions have been inversely related to refuge area in North American parks.

Reserves that originally may have been well sited to protect a vulnerable population and its habitat may, after climate change and population response, exist outside the now suitable range. Figure 8-3 illustrates this problem. Large reserves and buffer zones around reserves help to lessen these problems. Corridors between reserves lessen the problem of spatial isolation by allowing for some migration between reserves.



	PARK	AREA (km^2)	PERCENT OF ORIGINAL SPECIES LOST
1)	**Bryce Canyon**	144	36
2)	**Lassen Volcano**	426	43
3)	**Zion**	588	36
4)	**Crater Lake**	641	31
5)	**Mount Rainier**	976	32
6)	**Rocky Mountain**	1,049	31
7)	**Yosemite**	2,083	25
8)	**Sequoia-Kings Canyon**	3,389	23
9)	**Glacier-Waterton**	4,627	7
10)	**Grand Teton-Yellowstone**	20,736	4

Figure 8-2. Habitat area and loss of large animal species in North American parks (1986) (Newmark, 1987).

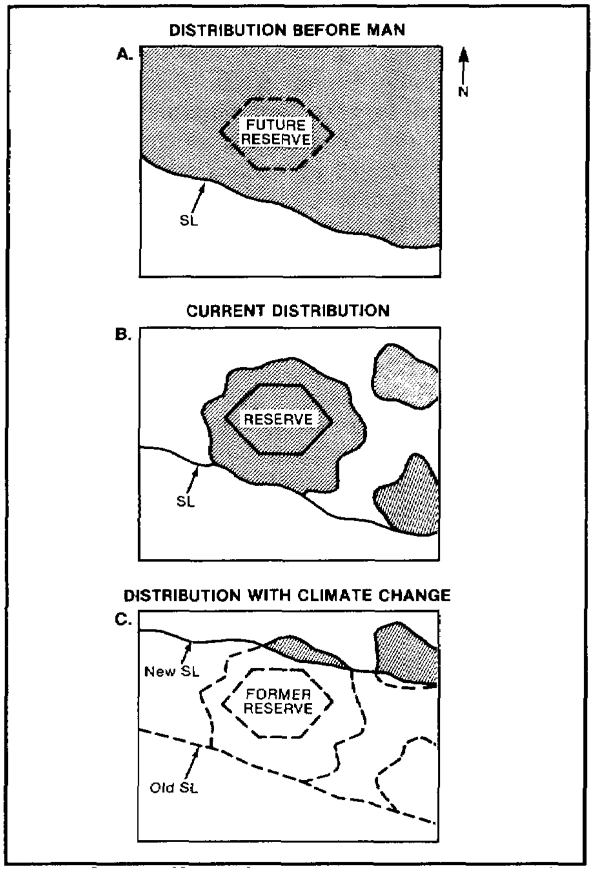


Figure 8-3. Effect of climate change on biological reserves. Hatching indicates the following: (A) species distribution before human habitation (SL indicates southern limit of species range); (B) fragmented species distribution after human habitation; (C) species distribution after warming (Peters and Darling, 1985).

Mountain Species

Just as species can migrate latitudinally, they can respond attitudinally to climate change by moving up or down a mountain slope. Species can often respond more easily to changing conditions on a slope because a shorter distance is required to migrate to achieve the same temperature change.

Among the problems associated with attitudinal migration are displacement of the species at the top (Peters and Darling, 1985). Also, with the increase in altitude, the area available for colonization usually becomes smaller, communities become isolated, and these smaller populations are more prone to extinction.

CLIMATE EFFECTS RESEARCH

This section reviews some previous studies of ecological response to past changes in climate, recent studies of potential response to climate change, and studies done for this report, which use climate change scenarios from general circulation models for a doubled CO_2 environment (see Table 8-1).

Forest Ecosystems

The tree species that make up any forest are major factors in determining the biological diversity found there. Trees provide a multitude of habitats and are the basis of much of the food web in a forest.

Changes in forest composition resulting from climate change (see Chapter 5: Forests) would have significant implications for biological diversity. Potential northerly range shifts of several hundred to a thousand kilometers may be limited by the tree species' ability to disperse. One possibility is that southern pine forests will move farther north into the regions currently occupied by mixed hardwood species. Some of these hardwood forests contain the highest tree species diversity found anywhere in the United States (Braun, 1950). If they migrated north, species would inevitably be lost, and overall biological diversity would substantially decrease.

If forests were disrupted by the extinction of the dominant tree species, the land would be invaded by weedy, opportunistic species. This would create a system with very low diversity, similar to that following logging. Ultimately, these new systems would not persist as succession took place, but the pattern of succession following the removal of a forest by rapid climate change is unknown.

Table 8-1. Studies Conducted for This Report and Cited in This Chapter

- Potential Responses of Great Lakes Fishes and Their Habitat to Global Climate Warming -Magnuson, Regier, Shuter, Hill, Holmer, and Meisner, University of Wisconsin (Volume E)

- The Effects of Global Climate Change on the Water Quality of Mountain Lakes and Streams - Byron, Jassby, and Goldman, University of California at Davis (Volume E)

- The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, HydroQual, Inc. (Volume A)

- Ecological Effects of Global Climate Change: Wetland Resources of San Francisco Bay -Josselyn and Callaway, San Francisco State University (Volume E)

- Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration - Livingston, Florida State University (Volume E) Tropical Forest Ecosystems

Tropical Forest Ecosystems

The greatest concentration of biological diversity in the world is in the rain forests of the Tropics (Wilson, 1988). Besides reducing diversity, deforestation contributes to disruption of the global carbon cycle by releasing CO_2 into the atmosphere and will directly affect the rate of climate change (Prance, 1986). Indeed, on a global scale, the problems of tropical deforestation, rapid climate change through (among other factors) increased CO_2 production, and the loss of biological diversity cane seen as aspects of the same problem.

Tropical forests are also important as wintering grounds for migratory birds coming from the United States and as sources of new knowledge, because the patterns of interactions between species and climate are at their most sensitive and complex there (Robinson, 1978; Janzen, 1986). The Tropics may provide important leading indicators of the ecological effects of climate change.

Freshwater Ecosystems

A study conducted by Magnuson et al. (Volume E) concludes that in most areas of the Great Lakes, climate warming would increase the amount of optimal thermal habitat for warm-, cool and coldwater fishes (see Chapter 15: Great Lakes). Although overall productivity would increase, overall biological diversity could decrease through intensified species interactions.

A study by Byron et al. (Volume E) on mountain lakes suggests that climate change would cause a range of impacts, including higher productivity, changes in species composition, and decreased water quality resulting from an increase in algal growth (see Chapter 14: California). Blumberg (Volume A) found that thermal stratification in Lake Erie could decrease dissolved oxygen levels.

The combined pressures of warmer waters, saltwater intrusion, and a rising sea level would significantly affect estuaries. The regional studies suggest that coastal estuaries would see a growth in marine species and a loss of some estuarine species. A study by Josselyn (Volume E) on the San Francisco Bay estuary suggests a decline in species that use the delta for spawning (see Chapter 14: California). Livingston (Volume E) concluded that crabs, shrimp, oysters, and flounder in the Apalachicola estuary could not survive the warming in the GISS and GFDL scenarios (see Chapter 16: Southeast).

Saltwater Ecosystems

In general, a warmer global climate would increase productivity in ocean fisheries, but the location and relative abundance of species are likely to change (Sibley and Strickland, 1985). Up to some threshold temperatures, such as 2°C (4°F), warmer ocean temperatures would increase ocean productivity in many species, but beyond that threshold, productivity could decline (Glantz, Volume J). It is likely that as productivity decreases, biological diversity would decrease as well. Warmer temperatures would most likely cause fish to migrate poleward, although many other factors, such as shifts in upwelling, may affect this.

Coral Reef Ecosystems

Coral reefs provide the structural base for the very biologically diverse reef ecosystems. Coral reefs in the Caribbean and the Pacific may be severely stressed as a result of warmer water temperatures and the rising sea level associated with climate change. Extensive bleaching of coral (the expelling of symbiotic algae in response to environmental stress) occurred in the Pacific after the 1982-83 El Nino (Glynn, 1984) and in the Caribbean following a summer of elevated water temperatures in 1987 (Roberts, 1987). Loss of the algae, the primary food source of the coral, is thought to kill coral, making the reef ecosystem vulnerable to erosion and physical devastation.

Coral reefs also will very likely be affected by sea level rise. Studies by Buddemeier and Smith (1988) and Cubit (1985) suggest that vertical accretion of reef flats eventually may be unable to keep up with an accelerating rise in sea level. Reef flats also may be subject to the stress of increasingly large waves, erosion, and sedimentation, which can inhibit coral growth (Buddemeier, 1988).

Arctic Ecosystems

Within the North American Arctics, plant size, vigor, and reproduction could be expected to increase with higher temperatures in the near term (years to decades). Some low-lying plants would most likely become upright, and there would be a northerly movement of the tree line and all vegetative zones (Edlund, 1986).

Over the longer term, however, rising temperatures may be a mixed blessing. Overall biological productivity is likely to increase, and some species may be able to increase their range. However, some arctic plant species are likely to be out-competed by invading species, and many others would face the same type of problem that mountaintop species face: they would have nowhere to go once they reach the Arctic Ocean. Thus, native arctic species may be especially at risk. Other arctic species may face their own problems. For example, caribou would be severely harmed if rivers do not freeze for periods long enough to allow for migration.

Migratory Birds

Migratory waterfowl are likely to experience very mixed effects as a result of warmer temperatures (Boyd, 1988). Herbivorous, arctic nesting species, such as geese, could benefit from the shortened winter season and from the increases in vegetation, in nesting habitat, and in ecosystem productivity (Harington, 1987). Smaller arctic nesting shorebirds, on the other hand, would be harmed by the encroachment of taller vegetation, potentially eliminating the preferred low-lying tundra breeding ground. Other effects on shorebirds could result from changes in ecosystem predator-competitor relationships and changes in the seasonal timing of such events as larval blooms, upon which these birds depend for nourishment while they are in a flightless stage and during migration (Myers, 1988).

Waterfowl that breed in the continental interior may suffer more than arctic nesters. Over half of all waterfowl in North America originate in the prairie pothole region, a large agricultural area riddled with ecologically productive permanent and semipermanent wetlands. Increased temperature and changes in seasonal precipitation could reduce the highly variable number of potholes (wetlands) in the area and could significantly impair the productivity of breeding ducks.

Because of the drought of 1988, over 35% of the seasonal wetlands within the prairie pothole region were dry during the breeding season (U.S. Fish and Wildlife Service, 1988). The Fish and Wildlife Service forecast that only 66 million ducks would migrate during the fall of 1988, a total of 8 million fewer than in 1987 and the second-lowest migration on record (Irion, 1988). The productivity index for mallards (number of young per adult) was 0.8, which was down by over 20% from the historical average (U.S. Fish and Wildlife Service, 1988).

Waterfowl and other migratory birds are likely to be affected on both ends of their migratory journey and at staging areas along the way. The loss of coastal wetlands, already an area of great concern in the United States, reduces the amount of habitat available to waterfowl, creating population pressures on a limited resource. Of the 215 million acres of wetlands in the coterminous United States at the time of settlement, fewer than 99 million acres (46%) remain (U.S. Fish and Wildlife Service, 1988). Loss of an additional 26 to 82% of existing coastal wetlands could occur over the next century as a result of a 1-meter rise in sea level, saltwater intrusion, and human development (see Chapter 7: Sea Level Rise). Loss of wintering habitat along the Gulf of Mexico would affect many waterfowl, including mallards, pintails, and snow geese.

The Tropics, the winter home for many species of migratory birds, may be significantly altered by rapid climate change. The need to protect a species in all parts of its range underscores the truly global nature of the effects of rapid climate change on biological diversity (Terborgh, 1974).

Endangered Species

Hundreds of species are currently listed as endangered in the United States, and several thousand await consideration for that status. These species are likely to be stressed further as a result of climate change.

Threatened and endangered species of the Southeast would be very susceptible to the impacts of sea level rise. Some species potentially at risk in that region include the Key deer, manatee, Florida panther, and Everglades kite (Breckenridge, 1988). Climate change could also greatly increase the number of rare, threatened, and endangered species in the United States.

Other Direct and Indirect Stresses

As plant and animal species experience increasing pressures from changes in temperature, precipitation, and soil moisture, so too will agriculture and urban water supplies. The changes that result from the human response to climate change may have the greatest impact on biological diversity. If the continental interior of North America dries, for example, wetlands that dry out may be cultivated, and our current uses of water resources may change. These secondary effects may significantly compound the loss of biological diversity.

NATIONAL POLICY IMPLICATIONS

Climate change presents new challenges for policymakers, regulators, and resource managers. Planning for climate change may help to minimize the disruption to natural systems and facilitate adaptation under changing conditions. Decisions will need to be made in an environment of increased pressure on many other resources.

Policies regarding rare and endangered species are likely to change as the number of species at risk greatly increases. As more species become stressed and potentially threatened by climate change, reevaluation of protection policies may be required. The tradeoffs between protection of individual species and species' habitats and the broader protection of biodiversity at the level of ecosystems may need to be reexamined. As a part of this question, decisions concerning whether to protect existing communities or to foster establishment of new communities may need to be made.

Management Options to Maintain Biological Diversity

Only a limited number of techniques are available for maintaining biological diversity. However, these techniques can be adapted and intensified to meet the potentially great impacts of rapid climate change.

Maintenance of Native Habitats

The most direct way to maintain biological diversity is to manage land to retain ecosystems, communities, and habitats. This already has been successfully undertaken on a broad scale by federal and state governments and by private organizations. Ecosystem conservation, especially as represented by the national parks and other large reserves, maintains much of our national biological diversity. These ongoing efforts will be the crucial first step for maintaining biological diversity in the face of climate change.

Land acquisition and management policies should take climate change into account. Climate change and the future requirements of whole ecosystems should be considered in siting and managing reserves. To preserve functioning ecosystems, large areas of land will be required. Preserves would need to be at least large enough to support self-sustaining populations. Lands that could be more important as future plant and animal habitats need to be identified and evaluated. Land managers should consider whether these lands should be set aside.

Although identification of appropriate future habitats is difficult and highly dependent on the future rate and extent of climate change, some areas, such as lowland areas adjacent to current wetlands, hold good potential for habitat protection.

To protect a species, alternative sites should be considered with regard to the ecological needs of target species under changing conditions. Siting reserves in mountainous areas is beneficial because it allows for the shorter-distance altitudinal shifts of adjustment to changing climate. Stream corridors, which can be effective avenues of dispersal for terrestrial as well as aquatic organisms, should be protected wherever possible. Providing corridors for migration between reserves also should enhance the ability of wildlife to adapt to climate change. Ideally, these corridors should be wide enough to maintain the ecosystem characteristics of the reserve in their center. Some species do not find the habitat conditions of narrow corridors suitable for migration.

The pressures caused by changing climate are likely to exacerbate competing land-use demands. Acquisition of land for preserving biological diversity will often be difficult, especially in areas where agriculture or forestry may be expanding. Flexible management strategies that reserve the possibility of land management for biological diversity in the future, while allowing for other use in the interim, hold potential for reducing resource conflicts and maintaining biological diversity. Creative approaches such as encouraging hedgerows, which may serve as migratory corridors, should also be considered.

Maintenance of Species in Artificial Conditions

When individual species are threatened with extinction, a possible option is to ensure that the species is propagated in captivity. Indeed, some rare species, such as the Pere David deer and the California condor, now exist only in captivity. This technique can be made to work for a variety of species, depending on their biology and the degree to which they successfully adapt to captive conditions. As more species become threatened with extinction due to climate change, the effort applied in this area may have to increase dramatically. However, only a tiny fraction of the nation's species can be maintained in this way. Existing seed bank programs also provide an important method for conserving plant genetic diversity.

Restoration of Habitat

Restoration ecology is a new discipline whose goal is to develop methods to restore damaged ecological communities to their prior unaltered state. Except in forestry, where reforestation has a longer tradition, restoration ecology has been in existence for only a few years. Nonetheless, it offers some real promise for ameliorating the effects of rapid climate change.

Normally, restoration is done at the site where the community previously existed and was altered or damaged. Historical and baseline information is used to manage the species in such a way as to eliminate unwanted new species and to encourage and possibly reintroduce native species.

Perhaps the theory and practice of restoration ecology could be expanded to include rebuilding natural communities on sites where they have not previously existed. This activity has not yet been attempted but may be necessary to save communities displaced by climate change. If the climate changes so that many of the key species of a community can no longer survive in their original range, and if the species are incapable of dispersing and establishing themselves elsewhere, then the artificial transplantation of components of entire communities may become necessary. This transplantation of communities would be a monumental task and could help to save much biological diversity, but it cannot possibly be undertaken on the scale necessary to preserve all species threatened by climate change. Restoration ecology can be useful for extending reserve boundaries and for providing migratory corridors.

Planning Options

While there are only a few management techniques to maintain biological diversity, many different groups in our society can implement them. These groups can be divided into the private and public sectors.

Many different groups in the private sector, ranging from private individuals to large conservation organizations, will have an interest in maintaining biological diversity. However, all would need information about the current and probable future state of biological diversity. The federal government may be able to play a role here by providing information on the state of biological diversity, including the systematics and distribution of species; on the genetic variability of species; and on the distribution of communities and ecosystems.

The four major federal land management agencies develop plans intended to lay out a comprehensive framework and direction for managing federal land. Land Resource Management Plans, required for each national forest, define the direction of management in the forest for the next 10 to 15 years. In addition, the Forest Service prepares 50-year plans, as required by the Resource Conservation Act. The National Park Service prepares a General Management Plan for each unit in the system that defines a strategy for achieving management objectives within a 10year time frame. A Statement for Management is also prepared for each national park and is evaluated every 2 years; this includes a determination of information needs. The Bureau of Land Management's (BLM) Resource Management Plans and the Fish and Wildlife Service's Refuge Master Plans are prepared and revised as needed for BLM resource areas and wildlife refuges (U.S. Department of the Interior, 1987). These periodic reviews of the management plans for public lands should include consideration of the possible effect of climate change on biodiversity.

Some federal land management agencies are beginning to devote resources to the climate change issue. The Forest Service, for example, has begun planning the Forest Atmosphere Interaction (FAI), which will be concerned with the relationship between the atmosphere and our national forests. The FAI has been designated a priority research program for the Forest Service.

The federal government manages an enormous amount of land and should consider management options to preserve biological diversity on much of that land. The major management techniques of habitat maintenance and restoration ecology could be applied by the agencies actively responsible for managing the nation's public lands.

RESEARCH NEEDS

The ability to protect biological diversity is severely restricted by a lack of knowledge regarding the rate of climate change, the precise nature of the change, how individual species will respond, and how ecological balances will shift. Research should be expanded in two areas: identification of biological diversity, and species interactions and biological diversity. New management options for biological diversity should be derived from these studies.

Identification of Biological Diversity

First and most important, an intensified, better coordinated research effort, involving both systematics (organism classification) and ecology, is required to identify the biologically diverse resources of our country. There should be more coordination to identify U.S. plants and animals, range maps, and habitat requirement information for those species.

The apparently simple task of identifying the species of plants and animals that exist in a given area is actually a major barrier to further understanding. Although common species are usually easy to identify, serious problems are often encountered in attempts to determine whether a widespread group is, for example, one or two species. For example, there is currently no federally sponsored Flora (listing of all known plants) of the United States.

Although it is necessary to describe the genetic diversity of our nation's species, it is difficult to do so in a direct fashion. What may be feasible is the further development of population genetic theory and of data that would predict the genetic diversity of a species based on species' properties, such as population size and habitat range variability.

The challenge in describing ecosystem diversity is to find the system of classification that best helps make decisions intended to minimize the loss of biological diversity. Such a system will most likely only be found through experience. For now, we should continue with the many different approaches of ecosystem classification, and we should look for the strengths of each.

Species Interactions and Biological Diversity

The second area to which research should be devoted is the direct effects of climate on species and the indirect interactions of species with other species dependent on climate. Comprehensive mapping of species' ranges along temperature and moisture gradients would provide valuable information. The direct effect of climate change on vegetation needs to be better assessed, and more estimates of species' dispersal rates would significantly improve our ability to identify species at greatest risk.

A variety of ecosystems within a diversity of climatic regions and terrains should be intensively studied using analog climate regions under changed climate conditions. Although an ecosystem's response under changing climate conditions will not be wholly predictable, modeling individual ecosystemic responses would enhance knowledge of the likely effects. Further research on how species interact and how trophic structures might change with climate would help predictive capabilities.

There should be further study on the question of the relationship between ecosystem function and species diversity to resolve the uncertainty in this area. Modeling the effect of climate change on ecosystem function and its relationship to diversity would help with predictive capabilities.

It will be impossible to study in detail even a fraction of the nation's species. The groups chosen for study either must be representative of many species or must possess some special properties (such as extreme sensitivity to climate change). The method of deciding which group to study is itself a major outstanding research question.

REFERENCES

Bolin, B., B. Doos, J. Jager, and R. Warrick, eds. 1986. The Greenhouse Effect, Climatic Change, and Ecosystems (SCOPE 29). Chichester, England: John Wiley and Sons.

Boyd, H. 1988. Impact of Climate Change on Arctic-Nesting Geese. Paper presented at Climate Institute Wildlife Symposium, Washington, DC; January 21.

Braun, E.L. 1950. Deciduous Forests of Eastern North America. New York: Hafner Publishing Company.

Breckenridge, R. 1988. Challenge of Assessing Climate Change Effects on Fish and Wildlife Resources in the Western United States. Paper presented at the Western Association of Fish and Wildlife Agencies, Western Division of the American Fisheries Society, Albuquerque, NM; July 10-13.

Brown, L., W. Chandler, A. During, C. Flavin, L. Heise, J. Jacobson, S. Postel, C. Shea, L. Starke, and E. Wolf. 1988. State of the World 1988. Worldwatch Institute. New York: W.W. Norton and Co., Inc.

Buddemeier, R. 1988. Impacts of Climate Change on Coral Reefs, Islands and Tropical Coasts. Paper presented at the Climate Institute Workshop on the Impact of Climate Change on the Third World, Washington, DC; March 24-25.

Buddemeier, R., and D. Hopley. 1988. Turn-Ons and Turn-Offs: Causes and Mechanisms of the Initiation and Termination of Coral Reef Growth. Paper presented for submittal to the Proceedings of the Sixth International Coral Reef Symposium, James Cook University, Townsville, Australia; August 8-12.

Buddemeier, R., and S. Smith. 1988. Coral Reef Growth in an Era of Rapidly Rising Sea Level: Predictions and Suggestions for Long-Term Research. Coral Reefs 7:51- 56.

CEQ. 1980. Council on Environmental Quality. Environmental Quality: Eleventh Annual Report. Washington, DC: U.S. Government Printing Office.

Cubit, J. 1985. Possible Effects of Recent Changes in Sea Level on the Biota of a Caribbean Reef Flat and Predicted Effects of Rising Sea Levels. Preprint from the Proceedings of the Fifth International Coral Reef Congress, Tahiti.

Edlund, S. 1986. Modern Arctic Vegetation Distribution and Its Congruence With Summer Climate Patterns. Environment Canada, Proceedings: Impact of Climatic Change on the Canadian Arctic.

Ford, Michael. 1982. The Changing Climate. London: George Allen and Unwin. Frye, R. 1983. Climatic Change and Fisheries Management. Natural Resources

Journal 23:77-96.

Glynn, P. 1984. Widespread Coral Mortality and the 1982-83 El Nino Warming Event. Environmental Conservation 11(2):133-140.

Harington, C. 1987. The Impact of Changing Climate on Some Vertebrates in the Canadian Arctic. Climate Institute, Proceedings of the First North American Conference on Preparing for Climate Change.

Hunt, C.B. 1972. Geology of Soils. San Francisco, CA: W.H. Freeman.

Hunt, C.B. 1974. Natural Regions of the United States and Canada. San Francisco, CA: W.H. Freeman.

Irion, R. 1988. Drought Helps Two Endangered Species Rebound, but It's a Dismal Year for Ducks. The Washington Post, August 1.

Janzen, D. 1986. The Future of Tropical Ecology. Annual Review of Ecology and Systematics 17:305324.

Jordan, W., R. Peters, and E. Allen. 1988. Ecological Restoration as a Strategy for Conserving Biological Diversity. Environmental Management 12(1):55-72.

Kiester, A.R., R. Lande, D.W. Schemske. 1984. Models of Coevolution and Speciation in Plants and Their Pollinators. American Naturalist 124(2):220243.

Leatherman, S. 1987. Effects of Sea Level Rise on Beaches and Coastal Wetlands. Climate Institute, Proceedings of the First North American Conference on Climate Change, Washington, DC, pp. 140-146.

Lovejoy, T. 1979. Refugia, refuges and minimum critical size: problems in the conservation of the neotropical herpetofauna. In: Duellman, W., ed. The South American Herpetofauna: Its Origin, Evolution and Dispersal. University of Kansas Museum Natural Hist. Monograph 7:1-485.

MacArthur, R., and E. Wilson. 1967. The Theory of Island Biogeography. Princeton, NJ: Princeton University Press.

Mayr, E. 1963. Animal Species and Evolution. Cambridge, MA: The Becknap Press of Harvard University Press.

Myers, J.P. 1988. Remarks to Climate Institute Wildlife Symposium. Washington, DC; January 21.

Myers, N. 1979. The Sinking Ark. New York: Pergamon Press.

Naveh, Z., and A. Lieberman. 1984. Landscape Ecology. New York: Springer-Verlag.

Newmark, W.D. 1987. A land-bridge island perspective on mammalian extinctions in western North American parks. Nature 325:430-432.

Peters, R., and J. Darling. 1985. The greenhouse effect and nature reserves. Bioscience 35(11):707717.

Prance, G.T. 1986. Tropical Rain Forests and the World Atmosphere. AAAS Selected Symposium No. 101. Boulder, CO: Westview Press, pp. xxi-105.

Regier, H., J. Holmes, J. Meisner. 1987. Likely Effects of Climate Change on Fisheries and Wetlands, With Emphasis on the Great Lakes. Climate Institute, Report for the First North American Conference on Preparing for Climate Change.

Roberts, L. 1987. Coral bleaching threatens Atlantic reefs. Science 238:1228-9.

Robinson, M.H. 1978. Is tropical biology real? Tropical Ecology 19(1):30-50.

Roush, J. 1986. Private action for public lands. The Nature Conservancy News 36(4):4-7.

Sibley, T., and R. Strickland. 1985. Fisheries: some relationships to climate change and marine environmental factors. Chapter 5. In: White, M.R., ed. Characterization of Information Requirements for Studies of CO_2 Effects. Washington, DC: U.S. Department of Energy.

Strain, B. 1986. The biosphere and links to climate. In: Rosenzweig, C., and R. Dickinson, eds. Climate-Vegetation Interactions. Proceedings of a NASA/Goddard Space Flight Center Workshop; January 27-29. Boulder, CO: Office for Interdisciplinary Earth Studies, University Corporation for Atmospheric Research.

Strain, B. 1987. Direct effects of increasing atmospheric CO_2 on plants and ecosystems. Tree 2(1):18-21.

Terborgh, J. 1974. Preservation of natural diversity: the problem of extinction prone species. BioScience 24(12):715-722.

Tiner, R. Jr. 1984. Wetlands of the United States: Current Status and Recent Trends. U.S. Fish and Wildlife Service. Newton Corner, MA: Habitat Resources.

Topping, J.C., and J. Bond. 1988. The Potential Impact of Climate Change on Fisheries and Wildlife in North America. Report of the Climate Institute to the U.S. EPA.

U.S. Department of the Interior. 1987. National Park Service and National Recreation and Park Association. Trends 24(2):2-43.

U.S. Fish and Wildlife Service. 1981. Endangered Means There's Still Time. Washington, DC: Department of the Interior, U.S. Fish and Wildlife Service.

U.S. Fish and Wildlife Service. 1988. Endangered Species Technical Bulletin; May.

Wilcox, B. 1982. Biosphere Reserves and the Preservation of Biological Diversity. Towards the Biosphere Reserve: Exploring Relationships Between Parks and Adjacent Lands. Kalispell, MT: Parks Canada and U.S. National Park Service; June.

Wilson, E.O. 1988. Biodiversity. Washington, DC: National Academy Press.

WRI. 1988. World Resources Institute. World Resources Report. New York: Basic Books.

CHAPTER 9
WATER RESOURCES

FINDINGS

Higher temperatures will most likely result in greater evaporation and precipitation; earlier snowmelt and reduced water availability in summer; and, during dry periods, more rapid declines in soil moisture and water levels, volumes, and flows. Although a general warming and global increase in precipitation are likely, the distribution of precipitation is highly uncertain and may change in unexpected ways. As a result, the frequency, seasonality, variability, and spatial distribution of droughts, water availability constraints, floods, and water quality problems will very likely change. Some regions could benefit from changing precipitation patterns, while others could experience great losses.

Although great uncertainty is associated with the projection of future hydrologic conditions and their water-use implications, we must be most concerned about current vulnerabilities to climate extremes that could become exacerbated under climate change. For instance, certain dry regions could become more vulnerable to drought as a result of higher temperatures, earlier snowmelt, and/or shifts in precipitation.

Impacts on Water Uses

- If climate in a given region were to become warmer and drier, water availability would decrease and water demand would increase, especially demand for irrigation and electric power production.

- Lower riverflows resulting from drier conditions could adversely affect instream uses such as hydropower production, navigation, aquatic ecosystems, wildlife habitat, and recreation.

- Lower streamflow and lower lake levels could cause powerplants to shift from once-through to evaporative cooling. New plants may also locate in coastal areas to obtain a water source that is reliable and that may be used without violation of thermal restrictions, although sea level rise could be a problem. This would have important implications for land use, transmission lines, and the costs of power.

- Where water availability is reduced, conflicts among users could increase. These include conflicts over the use of reservoir systems for flood control storage, water supply, or flow regulation; and conflicts over water rights among agricultural, municipal, and industrial users of water supply.

- Should extreme flood events become more frequent in a river basin as a result of earlier snowmelt and increased precipitation, activities located in the floodplain would endure more damages or could require more storage capacity (whether by construction, reallocation, or changes in operating procedures), often at the expense of other water uses.

Policy Implications

Water management responses to current vulnerabilities are available and in use, and can appropriately be brought into play to respond to changing hydrologic conditions. These responses include the following:

- Build new storage capacity, provided that the structures show positive net benefits under a variety of possible climatic conditions;

- Modify water system operations to improve performance under extreme conditions, to enhance recovery from extreme conditions, and to accept greater risk to low-valued uses to protect high-valued uses; and

- Encourage a reduction in water demand and an increase in water-use efficiency through conservation, water markets, water quality control, drought contingency planning, and coordinated uses of regional and interstate water resources, provided that such measures do not reduce the performance and recovery capabilities of supply systems.

IMPACTS OF CLIMATE CHANGE ON THE WATER RESOURCES IN THE UNITED STATES

Current Status of Water Resources

The potential effects of climate change on water resources must be examined within the context of the existing and projected supply of, and demands for, water.

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. On the average, 4,200 billion gallons per day (bgd) of precipitation fall on the lower 48 states. However, a large portion of this water (66%) evaporates, leaving 1,435 bgd (34%) for surface water runoff and groundwater recharge. Largely owing to weather variability, 675 bgd of the 1,435 bgd of runoff water in the coterminous United States is considered to be available for use in 95 years out of 100 (Figure 9-1).

Surface and groundwaters are managed by controlling and diverting flows through impoundments and aqueducts; by withdrawing water for such "offstream" applications as irrigation and municipal use; by regulating flows to maintain "instream" water quality and such uses as navigation, hydropower, and recreation; and by controlling flows under flood conditions to avoid loss of life, damage to property, or inconvenience to the public. Water may be "withdrawn" and returned to the source more than once, or "consumed" and not returned to the source.

In 1985, freshwater withdrawals for offstream uses totaled 338 bgd. Of the withdrawals, 92 bgd were consumed, mostly for irrigation. Withdrawals and consumption of freshwater by major offstream uses in 1985 are summarized in Figure 9-1.

Our investment in water infrastructure is substantial. Water supply for municipal and industrial use represented a $108 billion national investment in infrastructure in 1984 (National Council on Public Works Improvement, 1988). Government agencies and industries spent $336 billion (in constant 1982 dollars) from 1972 to 1985 (Farber and Rutledge, 1987) on water pollution abatement and control activities. In other areas, excess water periodically floods agricultural and urban areas, causing annual average damages valued at $3 billion (in constant 1984 dollars) during the past decade (National Council on Public Works Improvement, 1988).

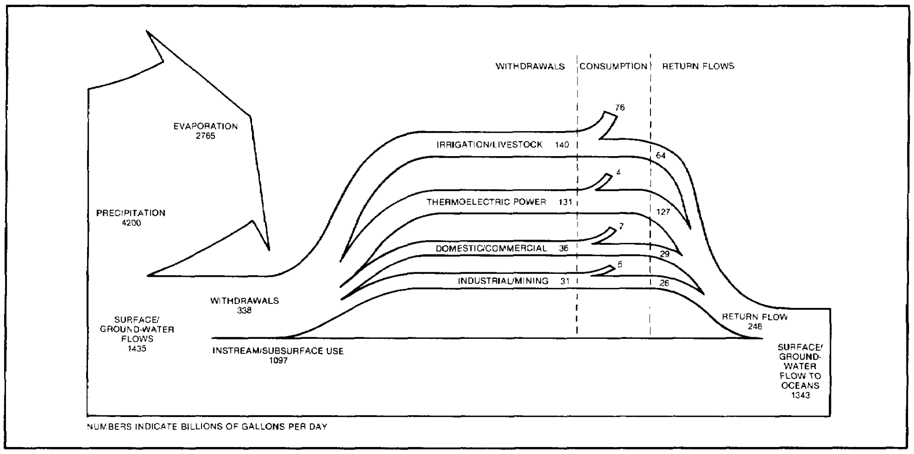


Figure 9-1. Water withdrawals and consumption by offstream uses, coterminous United States, 1985 (Solley et al., 1988).

On a national scale, water supplies are adequate, and water availability exceeds withdrawals and consumption. However, in some regions, the gap between demand for water and available supply is narrow, or the variability in water supply is high, or both. For example, average surface water withdrawal exceeds average streamflow in the Great Basin, Rio Grande, and Colorado River Basins. In these water-short basins, offstream water uses often conflict with instream uses, such as recreation and maintenance of environmental quality. Degraded water quality further limits water availability in many regions. Table 9-1 summarizes the current status of water supply by major river basin. The regions are delineated in Figure 9-2.

Table 9-1. Current Status of the Water Supply

River Basin	Average renewable supply (bgd)[a]	Withdrawal[b] (1985)	Consumption[b] (1985)	Reservoir storage[b]	Stream-flow exceeded 95% of time[c]	Ground-water overdraft
New England	78.4	11.7	0.9	15	62.4	0
Mid-Atlantic	80.7	29.5	2.1	11	62.2	1.2
South Atlantic- Gulf	233.5	13.5	2.1	15	55.5	6.2
Great Lakes	74.3	42.9	2.9	8	62.6	2.2
Ohio (exclusive of TN region)	139.5	22.3	1.5	13	59.0	0
Tennessee	41.2	22.3	0.8	24	77.0	0
Upper Mississippi (exclusive of MO region)	77.2	21.9	2.3	14	54.0	0
Mississippi (entire basin)	464.3	3.7	1.2	32	46.7	0.5
Souris-Red Rainy	6.5	4.3	1.9	110	32.1	0
Missouri	62.5	55.2	20.3	120	40.7	24.6
Arkansas-White-Red	68.6	22.3	11.7	41	36.5	61.7
Texas-Gulf	33.1	41.4	18.2	67	27.5	77.2
Rio Grande	5.1	109.8	43.7	182	33.3	28.1
Upper Colorado	14.7	51.4	16.3	229	39.0	0
Colorado (entire basin)	15.6	47.4	27.2	403	75.0	48.2
Great Basin	9.9	81.8	36.4	30	50.0	41.5
Pacific Northwest	276.2	12.9	4.5	20	70.7	8.5
California	70.2	53.6	29.9	49	44.0	11.5
Alaska	975.5	0.4	0.0	0.1	78.5	0
Hawaii	7.4	17.2	1.8	0.1	60.3	0
Caribbean	5.1	11.9	3.2	5	35.6	5.1

[a] Average renewable supply is defined as the average flow potentially or theoretically available for use in the region; units = billion gallons per day.

[b] Withdrawals, consumption, and reservoir storage are expressed as a percentage of the average renewable supply.

[c] As a percentage of average streamflow.

Source: U.S. Water Resources Council (1978); U.S. Geological Survey (1984); Solley et al. (1988).

Figure 9-2. Water resources regions (U.S. Geological Survey, 1985).

Water supply and use have changed significantly during the past decade. For the first time since 1950, when the United States Geological Survey began recording water withdrawals, national total fresh and saline water withdrawals dropped 10% from 1980 to 1985 (from 443 billion gallons to 399 billion gallons, of which 338 billion gallons were freshwater) (Solley et al., 1988). Increased conservation and water recycling in agriculture, industry, and energy production, slower growth in energy demand, and decline in availability of new water supply reduced or tempered water use in all sectors (Solley et al., 1988). Withdrawals declined by 7% in irrigation, by 33% in industry, and by 13% in thermal power during the same period. Of the major users, only municipal /domestic water supply increased (by 7%).

The value of instream uses has risen relative to that of offstream uses. Navigation and hydropower have retained their importance as society has begun to place greater value on wastewater dilution, ambient water quality, fish and wildlife habitats, and recreation. Higher values on instream uses have made diversion of water for such applications as agriculture in the West and for powerplant cooling in the East more difficult.

Climate Change, Hydrologic Conditions, and Water Resources

As shown in Figure 9-3, weather controls hydrologic conditions through precipitation (mean and frequency), runoff, snowmelt, transpiration and evaporation, soil moisture, and the variability of storms and drought. In turn, the ability to use water resources is greatly influenced by variability in hydrologic conditions.

Climate change will affect both the supply of and demand for water. Figure 9-4 outlines the major potential impacts of global warming and changes in precipitation on water resources.

If climate warms in the United States, there will likely be greater evaporation and, in turn, greater precipitation; earlier snowmelt and, in turn, reduced water availability in summer; and, during dry periods, more rapid declines in soil moisture and water levels, volumes, and flows. Over the very long term, groundwater availability may be affected by altered recharge rates. Transpiration may not increase as much because increased levels of carbon dioxide may shrink the stoma or pores of plants (Rosenberg, 1988).

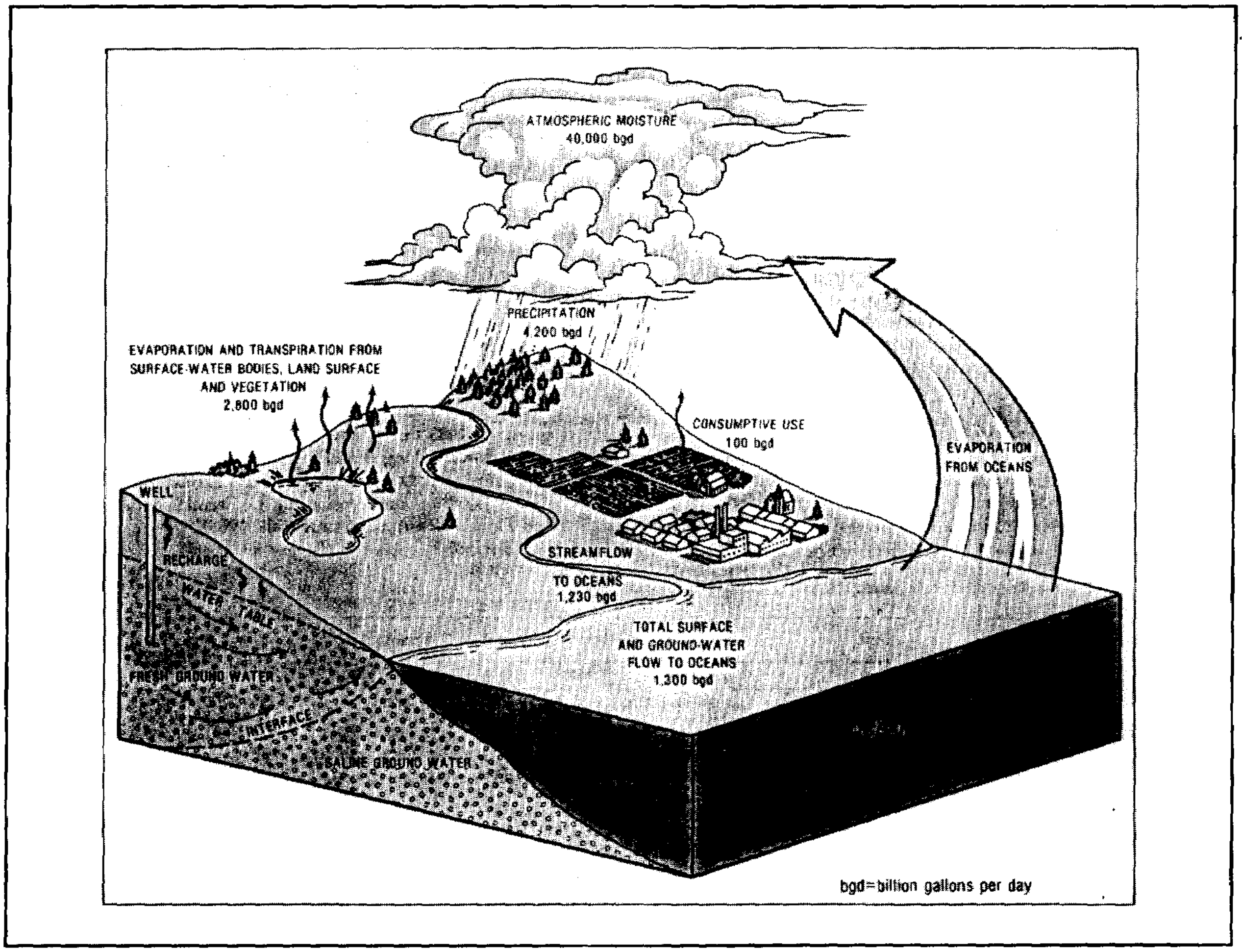
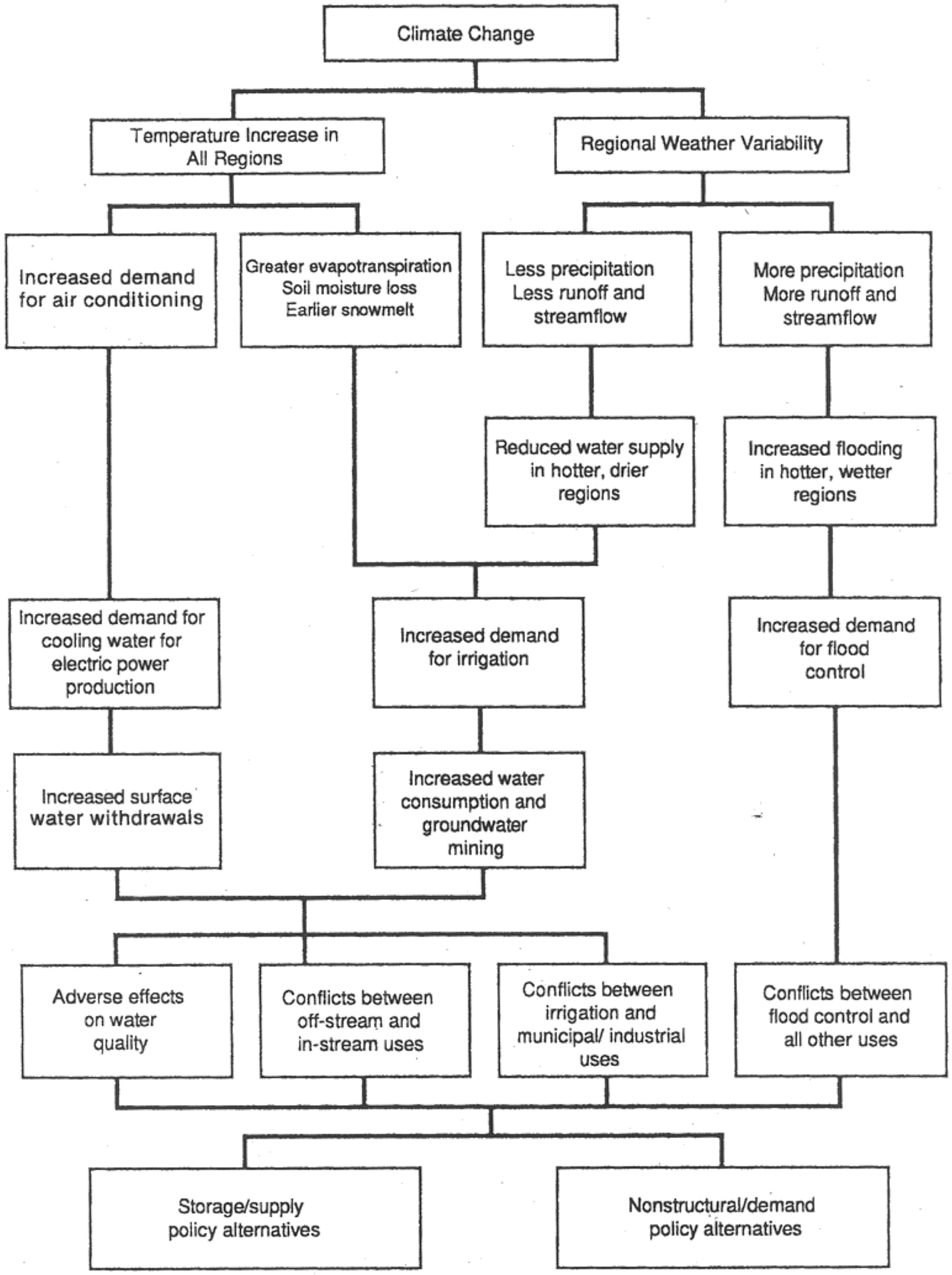


Figure 9-3. Hydrologic cycle showing the gross water budget of the coterminous United States (Langbein et al., 1949; Solley et al., 1983).

Although general warming is likely to occur, the distribution of precipitation is highly uncertain and may change in unexpected ways.

Earlier studies have shown that small changes in regional temperature, precipitation, and evaporation patterns can cause significant changes in water availability, especially in arid areas (see Nemec and Shaake,1982; Klemes and Nemec, 1985; Beran, 1986). Precipitation is more variable in arid than in humid areas. In addition, each degree of temperature increase causes a relatively greater decline in runoff and water availability in arid regions as compared with humid regions. If regional climate becomes warmer and drier, more vulnerability to interruptions in water availability may be observed.

As a result, the frequency, seasonality, variability, and spatial distribution of droughts, water availability constraints, floods, and water quality problems would probably change. In many locations, extreme events of dryness and flooding could become more frequent. Some regions may experience more drought conditions, others more flooding, others degraded water quality, and others a combination.



NOTE: Figure does not trace the impacts of reduced flows and increased evapotranspiration on navigation, hydropower, and the Great Lakes.

Figure 9-4. National impacts of climate change on water supply and demand.

Global warming may have a significant impact on the demand for water in some regions. Warmer temperatures may raise the demand for air conditioning in the South without a proportionate decrease in demand for electric heat. Increased demand for cooling water for electricity powerplants would result (see Chapter 10: Electricity Demand). Warmer temperatures may also prompt more farmers to irrigate crops (see Chapter 6: Agriculture).

Impacts of Climate Change on Water Uses

Models of global climate change do not yet provide reliable data to predict regional changes in the water supplies; however, we can indicate possible directions of impacts and the water uses and sectors affected. The following sections outline the potential impacts of climate change on offstream and instream water uses. The uses most likely to be affected are those currently vulnerable to water quantity and quality constraints:

- irrigation, the major source of withdrawals and consumption in the West;
- thermal power production, a major source of heat effluent and evaporative consumption, especially in the East;
- instream uses that depend on levels and flows; and
- domestic supplies that are vulnerable to hazardous and toxic substances in ground and surface water.

Table 9-2 highlights the vulnerability of major water uses in each region to climate change.

Irrigation

Irrigation accounts for 42% of freshwater withdrawals and 82% of freshwater consumption in the United States. Although irrigated land comprises about 10% of harvested cropland acreage nationwide, it contributes 30% of the value of cropland production. Many of these crops are fruits, vegetables, and specialty crops (U.S. Water Resources Council, 1978; Bajwa et al., 1987). The 17 western states account for 85% of the irrigated lands in the country (Bajwa et al., 1987).

Water-short western states are exploring numerous options for minimizing water requirements. Because of depleted groundwater supplies, the rising cost of obtaining groundwater, and the high cost and limited availability of sites for new surface water developments, irrigated acreage has stabilized or is declining in some areas of the West (Solley et al., 1988). Groundwater pumping for irrigation has already started to decline in the southern Great Plains States and in Arizona, although the impacts on production have been mitigated by the adoption of more efficient irrigation systems and by a switch to crops offering higher returns to wafer (Frederick and Kneese, 1989). In contrast, supplemental irrigation is rising in the Southeast, largely because of expansion in Georgia (Bajwa et al., 1987).

Table 9-2. Potential Regional Impacts of Climate Change on Water Uses: Areas of Vulnerability

Use	Pacific Northwest	California	Arid Western River Basins	Great Plains	Great Lakes	Mississippi	Southeast	Northeast
Irrigation	X	X	X	X			X	
Thermal power							X	X
Industrial		X	X					X
Municipal/domestic		X	X					X
Water quality			X	X	X	X	X	X
Navigation					X	X	X	
Flood control	X	X		X		X	X	
Hydropower	X	X			X		X	
Recreation					X		X	

Climate change may significantly affect agriculture. Summer drought and earlier runoff are likely to change agricultural practices and increase demands for irrigation in most areas east of the Rocky Mountains.

Thermal Power Generation

Thermal Power Generation Steam electric powerplants withdraw almost as much freshwater as irrigation but consume much less than irrigation. Although the freshwater withdrawn to produce the nation's electricity totals 131 bgd, only 4.35 bgd are actually consumed (Solley et al., 1988).

Future demand for water for power production will depend on energy demand, technology, and on federal and state regulations governing instream water quality, instream flow, and thermal pollution. Although a large amount of installed capacity exists along eastern rivers, freshwater withdrawals by powerplants in the East have decreased, and siting of plants in coastal areas has increased, so that by 1987, 30% of installed capacity in coastal areas used saline surface water (Solley et al., 1988). In addition, the thermal regulations have caused a shift in the design of new cooling systems from once- through cooling, which discharges heat back into the water sources, to evaporative cooling with towers and ponds (Breitstein and Tucker, 1986). Although evaporative cooling alleviates thermal pollution, it increases water consumption.

During droughts, federal and state regulations protecting instream uses and limiting thermal discharges may constrain withdrawals for powerplant cooling. In addition, powerplant water needs on some eastern rivers are so large that insufficient water may be available to dissipate heat during low-flow conditions (Hobbs and Meier, 1979).

Demand for electric power and construction of new generating capacity may increase as warmer temperatures raise air-conditioning use (see Chapter 10: Electricity Demand). If streamflows are reduced as a result of climate change, powerplants using once-through cooling could be adversely affected. Increased demand for power may reinforce existing trends in powerplant design toward evaporative cooling, and in powerplant siting toward coastal locations. With less water available, low- flow conditions may interrupt power production and may increase power production costs and consumer electricity prices.

Industrial Uses

Since 1954, self-supplied industry steadily used less and less water per unit of production (Solley et al., 1988). This decline was partly due to efficiencies achieved to comply with federal and state water pollution legislation that restricts the discharge of untreated water. The trend toward more efficient industrial water uses is continue.

In regions where flows are reduced, there could be a reduction in both the quantity and the quality of water available for industrial production. In addition, if the climate becomes drier, the potential for interruption of industrial supply will be increased.

Domestic Water Uses

Domestic uses account for 10% of total water withdrawn and 11% of consumption. Over the past 20 years, domestic water use has increased from 16 to 25 bgd owing to growth in the number of households, with little change in usage per household (Solley et al., 1988).

Most municipal water supply systems are designed to provide reliable water at all times (safe yield). However, urban growth depends upon developed water supply, which is approaching exhaustion in some areas. For instance, in the Southeast and parts of the West, a large percentage of municipal water supply comes from groundwater (U.S. Water Resources Council, 1978; Solley et al., 1988). These regions withdraw more groundwater than can be recharged; consequently, any increased drought caused by climate change could accelerate groundwater mining (see Chapter 14: California and Chapter 16: Southeast).

Municipalities in the West are purchasing irrigators' water rights to ensure adequate water supplies for urban growth. If climate change results in reduced municipal supply, this trend will continue or accelerate, leading to the loss of irrigated acreage.

In the East, Midwest, and Southeast, municipalities may be able to increase safe yield by repairing and replacing existing leaking water delivery systems and by consolidating fragmented water supply districts. These actions could provide the margins of safety necessary to accommodate climate change.

Navigation

If riverflow and lake levels became lower, navigation would be impeded. Systems that are particularly vulnerable are those with unregulated flows or levels and high traffic, such as the Mississippi River and the Great Lakes. The effects of dry conditions and reduced water levels on barge traffic on the Mississippi in 1988 illustrate the potential impacts of climate change.

Hydropower

Because of the decline in water availability that could result from climate change, hydropower output and reliability, which depend on flows, could decline in the West and the Great Lakes. If the Southeast became drier, it could face the same problems unless it sacrificed water supply reliability to maintain hydropower production.

Recreation

If the Southeast becomes drier, there may be an increase in the conflict among water uses, especially over reservoir releases and levels in the Tennessee Valley and the Lake Lanier, Georgia, system. The conflicts are among flood control, which relies on storage; recreation, which depends on stable reservoir pool elevations; and downstream uses and water supply, which depend on flows.

Climate Change and Water Quality

Water quality directly affects the availability of water for human and environmental uses, since water of unsuitable quality is not really "available." Likewise, water quality in the nation's rivers, lakes, and streams depends in part on water quantity. Water supply is needed for dilution of wastewaters that flow into surface and groundwater sources. Freshwater inflows are needed to repel saline waters in estuaries and to regulate water temperatures in order to forestall changes in the thermal stratification, aquatic biota, and ecosystems of lakes, streams, and rivers.

The Federal Clean Water Act of 1972 and subsequent amendments ushered in a new era of water pollution control. Massive expenditures for treatment facilities and changes in water-use practices by government and industry have decreased the amount of "conventional" water pollutants, such as organic waste, sediment, oil, grease, and heat, that enters water supplies. Total public and private, point and nonpoint, and capital and operating water pollution abatement and control expenditures from 1972 to 1985 totaled $336 billion in 1982 dollars (Farber and Rutledge, 1987).

Nevertheless, serious surface water quality problems remain. Groundwater pollution problems, especially toxic contamination and nonpoint source pollution, are receiving increased recognition (U.S. EPA, 1987b).

One-third of municipal sewage treatment plants have yet to complete actions to be in full compliance with the provisions of the Clean Water Act (U.S. EPA, 1987a). Federal and state regulation of previously unregulated toxic and hazardous water pollutants has just begun. In the West, irrigation has increased the salinity levels in the return water and soils of several river basins (the lower Colorado, the Rio Grande, and the San Joaquin) to an extent that threatens the viability of irrigation (Frederick and Kneese, 1989).

Should climate change involve reduced flows, less freshwater may be available in some regions for diluting wastewater salt and heat, especially in lowflow periods (Jacoby, 1989). Dissolved oxygen levels in the water would decline while temperature and salinity levels would increase, affecting the viability of existing fish and wildlife. Increased thermal stratification and enhanced algal production due to higher temperatures may degrade the water quality of many lakes (see Chapter 15: Great Lakes; Blumberg and DiToro, Volume A). Finally, the combination of declining freshwater availability and rising sea level would move salt wedges up estuaries, changing estuarine ecology and threatening municipal and industrial water supplies. On the other hand, should climate change involve increased flows, greater dilution of pollutants would be possible in some regions.

Groundwater is the source for over 63% of domestic and commercial use (Solley et al., 1988). Although only a small portion of the nation's groundwater is thought to be contaminated, the potential consequences may be significant and may include cancer, damage to human organs, and other health effects (U.S. Congress, 1984).

Adequate recharge of aquifers is needed not only to perpetuate supplies but also to flush contaminants. Should climate change result in reduced flows and reduced recharge, the quality as well as the available quantity of groundwater could be adversely affected.

Climate Change and Flood Hazards

Because of the buffering and redundancy designed into large structures, major federal flood control projects may be able to contain or mitigate the impacts of more frequent severe floods. However, continued performance for flood control may come at the expense of other uses. For example, drawing down the levels of reservoirs to contain floodwaters from anticipated increases in precipitation or earlier snowmelt may curtail water availability for water supply. (This aggravated conflict is a distinct possibility in California, for example; see Chapter 14: California.)

The major concern with existing dams and levees is the consequence of failure under extreme conditions. For instance, an increased probability of great floods, whether due to urbanization of upstream watersheds or to climate change, would cause dams with inadequate spillways to fail. (Spillways are designed to prevent dam failure through overtopping.)

The majority of large dams that provide substantial flood storage are in good condition. The National Dam Safety Inventory shows that the overall condition of the U.S. Army Corps of Engineers' more than 300 flood control reservoirs is sound (National Council on Public Works Improvement, 1988). In addition, the spillways of many large dams are designed to pass a "probable maximum flood" (an extreme flood event much greater than the 100-year flood).

Smaller structures, such as urban drainage culverts and sewers and local flood protection projects, are currently more susceptible to failure and are in poorer condition than large structures (National Council on Public Works Improvement, 1988). One-third of the non-federal flood control dams inspected under the national non-federal dam program were found to be unsafe, mostly owing to inadequate spillways (National Council on Public Works Improvement, 1988). The capacity of these non-federal, smaller, mostly urban flood control and stormwater structures is more likely to be exceeded. Urbanization upstream from many dams and water control structures is already resulting in increased impervious surfaces (such as pavement) and increased peak runoff, making some structures increasingly vulnerable to failure.

Climate Change and Conflicts Among Water Uses

There is no doubt that climate change has the potential to exacerbate water availability and quality problems and to increase conflicts between regional water uses as a result. The foregoing discussion has highlighted a number of such conflicts:

- conflicts between instream and offstream uses;
- conflicts among offstrearn uses, such as agriculture, domestic use, and thermal power production;
- conflicts between water supply and flood control in the West;
- conflicts between all uses and recreation in the Southeast; and
- conflicts between thermal power production and instream uses, especially in the East.

In some areas, increased precipitation due to climate change could alleviate water quality/quantity problems and conflicts, but only after water infrastructure is modified to accommodate the increased probability of extreme events.

REGIONAL IMPACTS OF CLIMATE CHANGE

Water resources supply and management occurs at the regional, river basin, state, and local levels. To be of use to water resources decisionmakers, climate change models and forecasts need to address regional impacts.

The regional studies conducted by the U.S. Environmental Protection Agency for this document (see Table 9-3) examine the potential regional impacts

Table 9-3. Regional Water Resource Studies

California

- Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin, California - Lettenmaier, University of Washington (Volume A)
- Methods for Evaluating the Potential Impact of Global Climate Change - Sheer and Randall, Water Resources Management, Inc. (Volume A)
- The Impacts of Climate Change on the Salinity of San Francisco Bay - Williams, Philip Williams & Associates (Volume A)

Great Lakes

- Effects of Climate Changes on the Laurentian Great Lakes Levels - Croley, Great Lakes Environment Research Laboratory (Volume A)
- Impact of Global Warming on Great Lakes Ice Cycles - Assel, Great Lakes Environment Research Laboratory (Volume A)
- The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, HydroQual, Inc. (Volume A)
- Potential Climatic Chances to the Lake Michigan Thermal Structure - McCormick, Great Lakes Environment Research Laboratory (Volume A)

Great Plains

- Effects of Projected CO_2 -Induced Climate Changes on Irrigation Water Requirements in the Great Plains States - Allen and Gichuki, Utah State University (Volume C)

Southeast

- Potential Impacts of Climatic Change on the Tennessee Valley Authority Reservoir System - Miller and Brock, Tennessee Valley Authority (Volume A)
- Impacts on Runoff in the Upper Chattahoochee River Basin - Hains, C.F. Hydrologist, Inc. (Volume A)
- Methods for Evaluating the Potential Impact of Global Climate Change - Sheer and Randall, Water Resources Management, Inc. (Volume A)

of climate change. (With the exception of Allan and Gichuki (Volume C), all studies listed in Table 9-3 are found in Volume A.) The studies use scenarios generated from up to four global circulation models (GCMs) as their starting points (see Chapter 4: Methodology) and match them with regional or subregional water resource models. This section reviews the findings from the studies on California, the Great Plains, the Great Lakes, and the Southeast; from previous studies of the impacts of climate change on these and other regions; and from previous hydrologic studies and models of individual river basins.

The GCMs do not yet provide definitive forecasts concerning the frequency, amount, and seasonality of precipitation and the regional distribution of these hydrologic effects (see Chapter 2: Climate Change; Chapter 3: Variability; Chapter 4: Methodology; Rind and Lebedeff, 1984; Hansen et al., 1986; Gleick, 1987; Rosenberg, 1988). The uncertainty of the forecasts is partially due to the limitations and simplifications inherent in modeling complex natural and manmade phenomena. Modeling efforts are made more difficult by the feedbacks and interconnections between changes in temperature; and the amount and frequency of precipitation, runoff, carbon dioxide, growth and transpiration of foliage, cloud cover, ocean circulation, and windspeed.

However, the regional studies commissioned for this report are a significant step in the effort to bring GCM and regional water resources models together to examine the regional impacts of climate change.

The West

The arid and semiarid river basins west of the Mississippi River have significant surface and groundwater quantity and quality problems and are vulnerable to restricted water availability. Total water use exceeds average streamflow in 24 of 53 western water resource regions (U.S. Water Resources Council, 1978), with the majority of the West's water withdrawals going to irrigation. Surface and groundwater quality in the West have deteriorated as a result of low flow, salts concentrated by irrigation, and pesticide use. The West also depends upon nonrenewable groundwater supplies for irrigation (Solley et al., 1988).

Climate change may exacerbate water shortage and quality problems in the West. Higher temperatures could cause earlier snowmelt and runoff, resulting in lower water availability in the summer. Some GCM scenarios predict midsummer drought and heat, less groundwater recharge, and less groundwater and surface water availability for irrigation in the middle latitudes of the country. The sensitivity analyses conducted by Stockton and Boggess (1979) indicated that a warmer and drier climate would severely reduce the quantity and quality of water in arid western river basins (Rio Grande, Colorado, Missouri, California) by increasing water shortages. Water shortages and associated conflicts between instream and offstream uses, between agricultural and urban/industrial water uses, and between flood control and other water uses of reservoirs may be expected under these scenarios. Hydropower output also would decline as a result of lower riverflow.

Pacific Northwest

The competition for water for irrigation, hydropower, and fisheries habitat is increasing in the Pacific Northwest (Butcher and Whittlesey, 1986). Climate change may alter the seasonality and volume of precipitation and snowmelt, increasing the risk of flooding, changing reservoir management practices, and affecting the output and reliability of hydroelectric power production and the availability of water for irrigation.

California

The diversion of water from water-rich northern California and from the Colorado River to southern California via federal and state systems of dams, aqueducts, and pumping stations has transformed California into the nation's leading agricultural state and has made possible the urbanization of southern California. Irrigation accounted for 83% of the total value of California's agricultural output in 1982 (Bajwa et al.,1987). Because of this high economic dependence on water in an arid area, southern California is vulnerable to droughts and any altered temporal pattern of runoff that may be caused by atmospheric warming.

Total annual runoff from the mountains surrounding the Central Valley is estimated to increase slightly under GCM scenarios, but runoff in the late spring and summer maybe much less than today because higher temperatures cause earlier snowmelt (Lettenmaier, Volume A). The volume of water from the State Water Project may decrease by 7 to 16% (see Chapter 14: California; Sheer, Volume A). Existing reservoirs do not have the capacity to increase storage of winter runoff and at the same time to retain flood control capabilities. In addition, flows required to repel saline water near the major freshwater pumping facilities in the upper Sacramento-San Joaquin River Delta may have to be doubled as a result of sea level rise, further reducing water available to southern California (Williams, Volume A).

Decreases in water availability may also reduce hydroelectric power produced in California. In the 1976- 77 drought, hydroelectric production in northern California dropped to less than 50% of normal, a deficiency relieved by importing surplus power from the Pacific Northwest and by burning additional fossil fuels at an approximate cost of $500 million (Gleick, 1989).

Colorado, Rio Grande, and Great Basins

Total consumption is more than 40% of renewable supply in these river basins. The Colorado River Basin has huge reservoir storage, but demand exceeds supply in the lower half of the basin. Ordinarily all of the Colorado River's water is consumed before it reaches the Gulf of California in Mexico. The Colorado River Compact of 1922, the 1963 Supreme Court decision in Arizona v. Califomia, the treaties with Mexico of 1944 and 1973, and other agreements allocate Colorado River water to seven states and Mexico (Dracup, 1977). Some studies show that the Upper Colorado region will use all of its allocation by the year 2000, reducing water hitherto available to lower Colorado and California (Kneese and Bonem, 1986).

Climate change may further reduce the availability of water in these basins. A model by Stockton and Boggess (1979) of a 2 C temperature increase and a 10% precipitation decrease shows decreases in the water supply in the upper Colorado and the Rio Grande of 40 and 76%, respectively.

Great Plains

The southern Great Plains States of Kansas, Nebraska, Oklahoma, and Texas produce almost 40% of the nation's wheat, 15% of its corn, and 50% of its fattened cattle (see Chapter 17: Great Plains). The region heavily depends on groundwater mining (when pumping exceeds aquifer recharge) for irrigation. The region was severely affected during the "Dust Bowl" years of the 1930s and suffered from severe drought in 1988.

Because of the greater reliability in irrigated yields relative to dryland yields, the demand for irrigation could rise (Allen and Gichuki, Volume C; Adams et al., Volume C). Thus, while total agricultural acreage could decrease, irrigated acreage and groundwater mining may increase in the southern Great Plains. Greater demand may be placed on the Ogallala Aquifer, which underlies much of the region, causing further mining of the aquifer.

Great Lakes

Based on analyses for this report (Croley and Hartmann, Volume A), higher temperatures may overwhelm any increase in precipitation and may evaporate lakes to below the lowest levels on record. However, changes in Great Lakes evaporation under climate change are highly uncertain and depend on such variables as basinwide precipitation, humidity, cloud cover, and windspeed. Under a possible set of conditions, lake levels could rise. The winter ice cover would be reduced but would still be present, especially in shallow areas and northern lakes (Assel, Volume A). Navigation depths, hydropower output, and water quality all would be adversely affected, but losses of existing shorelands from erosion would be reduced as a result of lower lake levels (see Chapter 15: Great Lakes).

Mississippi River

The Mississippi River historically has been affected by both spring floods and drought. In 1988, low flows due to drought received national attention. Low flows disrupt navigation, permit saltwater intrusion into the drinking water of southern Louisiana cities, reduce the dilution of contaminants transported from upstream locations, and reduce the inflow of water to the vast Mississippi Delta wetlands (see Glantz, Volume J).

Northeast

Although the Northeast is humid, cities and powerplants demand large amounts of water at localized points in a watershed, necessitating storage and interbasin transfers. Because of the small amount of storage in the Northeast, the region is vulnerable to prolonged drought. No new major storage has been built in the Northeast during the past 20 years, except the Bloomington Dam on the Potomac River. Water supply in lower New England, New York, and Pennsylvania, and power production in the Northeast, remain vulnerable to drought, which may occur more frequently (Schwartz, 1977; Kaplan et al., 1981). During periodic droughts in the Northeast, such as those in 1962-65 and 1980-81, instream flow regulations ration water and threaten shutdowns of electrical powerplants (U.S. Army Corps of Engineers, 1977; Schwartz, 1977; Kaplan et al., 1981).

Southeast

In the Southeast, the experience with drought in recent years is increasing the use of groundwater and surface water for irrigation and is prompting farmers to consider shifting crops. In Georgia, for instance, the use of groundwater for irrigation has grown quite rapidly. However, the GCMs disagree on whether the Southeast may become wetter or drier (see Haines, Volume A; Miller and Brock, Volume A). Most reservoirs in the area have sufficient capacity to retain flood surges and to maintain navigation, hydropower, water supply, and instream uses (e.g., dilution, wildlife) under both wetter and drier conditions (see Chapter 16: Southeast; Sheer and Randall, Volume A). However, drier conditions would pose conflicts between recreational uses (which would be hurt by changes in reservoir levels) and all other instream and offstream uses.

Should the Southeast become drier, a decline in the inflow of freshwater could alter the estuarine ecology of the gulf coast, which may be most vulnerable to sea level rise (see Chapter 16: Southeast).

POLICY IMPLICATIONS

Decreases in water availability and quality, increased risk of flood damages, and the exacerbation of conflicts between water users competing for an increasingly scarce or difficult to manage resource are the major potential impacts of a global warming trend on the nation's water resources. How will we manage water resources given the possibility of change and uncertainties about its nature and timing?

Policy approaches to water resources may be grouped under supply (or structural) approaches and demand (or nonstructural) approaches. Supply approaches mitigate hydrologic variability and climate change; demand approaches modify behaviors that create vulnerability to such change. For example, water shortages may be addressed either by developing surface water storage capacity and improving the quality of water from available sources (supply approaches), or by decreasing water use and consumption (a demand approach).

Many of the policy approaches discussed below have been recommended by water resource experts for 20 years and are in use to address existing water problems and vulnerabilities. The potential of climate change provides another reason for expanded use of these approaches.

Supply and Structural Policy Approaches

The supply-related policy approaches to water resources include design for uncertainty, surface water development, and optimization of water resource systems.

Design for Uncertainty

Most water resource decisions in the past have been based on the assumption that the climate of a region varies predictably around a stationary mean. Water managers develop water resources plans based on statistical analyses of historical climatological and hydrologic data. However, the frequency of extreme events, which has been assumed to be fixed or to be modified only by the urbanization of watersheds, may be changed significantly by altered climatic conditions.

In addition to being uncertain about hydrologic conditions, we are uncertain about future demographic, economic, and institutional factors that affect offstream water uses and social and economic values attached to instream uses. As an example, water withdrawals in 1985 declined overall from 1980, falling far short of projections made starting in 1960 and as recently as 1978 (Solley et al., 1988).

Finally, we are uncertain about how our economic, regulatory, and institutional systems will respond to climate change in the absence of concerted governmental action. It would be a mistake to attempt to project the impacts of climate change simply by superimposing projected future hydrologic conditions on today's social systems.

The planners and designers of water resources must address such uncertainties. Three types of response are often used to address conditions of great uncertainty:

- Avoid inflexible, large-scale, irreversible, and high-cost measures; opt for shorter term, less capital-intensive, smaller scale, and incremental measures.

- Conduct sensitivity analysis and risk-cost exercises in the design of structural and management systems to address the potential range of climate change impacts. Sensitivity analysis describes the sensitivity of projections to variables affecting their accuracy; risk-cost analysis identifies the costs, for various conditions other than those projected, associated with underdesign or overdesign of a structure. The consideration of hydrologic extremes and the use of risk analysis in the design of specific projects to mitigate the adverse consequences of hydrologic variability may incidentally mitigate many of the physical impacts of climate change (Hanchey et al., 1988).

- Design structures and systems for rare events. Matalas and Fiering (1977) found that many large systems have substantial redundancy (margins of safety) and robustness (ability to perform under a variety of conditions) that enable them to adapt technologically and institutionally to large stresses and uncertain future events.

Although the principle of design for rare extremes may provide robustness, it has a cost and may conflict with the principle of maximizing the economic return from a project. Most public and private water developers subject projects to "net present value" or "internal rate or return" analyses. These analyses discount future benefits relative to present benefits. If a high discount rate is used in decisionmaking, conditions beyond 10 or 20 years may have little impact on design and investment decisions (see Chapter 19: Preparing for a Global Warming; Hanchey et al., 1988).

Surface Water Development

Surface water structures increase developed or available water supply, provide for the regulation of flows for instream uses, prevent flooding, or perform some combination of these functions. These structures include dams, reservoirs, levees, and aqueducts. Because of high costs of construction, adverse impacts on the environment, the limited number of sites available for new structures, and opposition by citizen groups, the trend during the past decade has been away from large excess-capacity, capital- intensive projects. Only the Central Utah Project and the Central Arizona Project have gone forward in recent years. Only one major project in the Northeast has been completed in past 20 years: the Bloomington Dam on the Potomac River. In 1982, California citizens voted down funds for the proposed Peripheral Canal that would have permitted increased diversion of water from north to south in the state. In addition, the national trend toward increased local/state financing and reduced federal fmancing for projects has reduced funds available for large projects (National Council on Public Works Improvement, 1988).

These current trends in water resources management may be reevaluated in light of possible new demands for developed water caused by climate changes. Pressure to build proposed projects such as the Narrows Project in Colorado, the Garrison Diversion in North Dakota, the Peripheral Canal in California, and structures to divert water from northern New England to southeastern Massachusetts may be renewed if droughts reoccur or demand increases. The pace at which existing projects are upgraded, modified, or expanded may also accelerate.

Optimization of Water Resource Systems

Water resources can be managed to maximize the water availability from a given resource base such as a dam, watershed, or aquifer. Adoption of systemwide strategies for a large-scale water system may allow for substantial operating flexibility related to releases of stored water. This flexibility can have an enormous influence on the overall performance and resilience (recovery abilities) of the system, and may provide additional yields that mitigate the impacts of climate change. For example, the U.S. Department of the Interior's Bureau of Reclamation (1987) is adopting operational, management, or physical changes to gain more output from the same resources. Water management agencies nationwide are implementing methods to protect groundwater recharge areas and to use ground and surface waters conjunctively (U.S. EPA, 1987b). Watershed management practices also affect water supply; for example, water yields can be significantly affected by timber harvest practices.

In the East, consolidation of or coordination among fragmented urban water supply authorities can achieve economies of scale in water delivery, decrease the risk of shortage in any one subsystem within a region, increase yields, and provide effective drought management procedures. Sheer (1985) estimated that coordinated water authority activities in the Potomac River basin eliminated the need for new reservoirs, saving from $200 million to $1 billion.

River basin and aquifer boundaries in many cases traverse or underlie portions of several states. Regional and interstate cooperation to manage water resources has a long tradition in some U.S. river basins. Although numerous opportunities exist for additional coordination of water management between states, within basins, or between basins, the agreements required for regional compacts and operating procedures and sharing of water supplies may require substantial and lengthy negotiations.

Several interstate water authorities have significant water allocation authority. For example, the Delaware River Basin Commission allocates water to users in the Delaware Basin and transfers it to New York City under authority of a 1954 Supreme Court ruling (347 U.S. 995) and federal legislation, which established the Commission in 1961 and granted it regulatory, licensing, and project construction powers. Similarly, water authorities in the Washington, D.C., metropolitan area operate Potomac River water supply projects as integrated systems under a 1982 agreement. Both the Delaware and Potomac regional compacts include provisions for drought allocations. (See Harkness et al., 1985, for management actions taken by the Delaware River Basin Commission during a 1984-85 drought.)

Demand Management and Nonstructural Policy Approaches

Demand-related adaptations encourage a reduction in water demand and an increase in water use efficiency through pricing, market exchange of water rights, conservation, protection of water quality, education and extension service assistance, technological innovation, and drought management planning. Policies that discourage activities in floodprone areas are the nonstructural counterparts for reducing flood damage.

Water Pricing, Water Markets, and Water Conservation

In the past, many people considered that water was too essential a resource or too insensitive to price to allow market forces to allocate its use, especially during shortages. Policy took the form of direct controls and appeals to conserve (Hrezo et al., 1986). In recent years, greater attention has been given to market-based policies and mechanisms that allocate limited water supplies among competing uses and promote water conservation.

Water prices that reflect real or replacement costs and the exchange of water rights by market mechanisms can promote conservation and efficient use. Since water use is sensitive to price (Gibbons, 1986) water users faced with higher prices will conserve water and modify their technologies and crop selection to use less without substantial reduction in output. If there is a market for water rights, those willing to pay more may purchase rights from those less willing to pay. As a consequence, water will be transferred out of marginal uses and will be conserved.

Three related pricing and conservation approaches are irrigation conservation, municipal and industrial water use, and water markets and transfers.

Irrigation Conservation

Relatively small reductions in irrigation demand can make large amounts of water available for urban and industrial uses. For instance, nearly 83% of the withdrawals and 90% of the consumptive use of western water is for irrigation. A 10% reduction in irrigation use would save 20 million acre-feet (maf) in water withdrawn and 10 maf in water consumed annually, effectively doubling the water available for municipal and industrial uses in the West (Frederick, 1986). (For comparison, the average annual flow of the Upper Colorado River Basin is 15 maf.)

Inexpensive water was a key factor in the settlement of the West and the expansion of agriculture (Frederick, 1986). The Bureau of Reclamation was established early in this century to promote the development of irrigation in the West. The Bureau provides irrigation for about 11 million acres, more than one-fifth of the total irrigated acreage. Since the Bureau accounts for nearly one-third of all surface water deliveries and about one-fifth of total water deliveries in the 17 western states, actions by the Bureau to use this water more efficiently have an impact throughout the West (Frederick, 1986).

In the past, demand for Bureau water was not based on the real cost of the water, because more than 90% of the Bureau's irrigation projects have been subsidized, and payments on some projects no longer even pay for operation and maintenance (Frederick and Hansen, 1982). Irrigators fortunate enough to receive such inexpensive water may have little or no incentive to conserve. However, the Bureau's more recently stated objectives include revising their water marketing policy, promoting conservation, and pricing water to reflect its real cost (U.S. Department of the Interior, 1987).

Municipal and Industrial Water Use

Municipalities throughout the country are finding it difficult and expensive to augment their supplies to meet the demands of population and economic growth and are finding that users would rather use less than pay more (Gibbons, 1986). Traditional average-cost pricing provides adequate service to customers and adequate returns to water companies, but is being reevaluated because it tends to cause overinvestment in system capacity (U.S. Congress, 1987). Marginal-cost pricing (charging for the cost of the last-added and most expensive increment of supply) or progressive-rate pricing (charging more per unit to users of large amounts) can reduce domestic and industrial water consumption because water use is sensitive to price (Gibbons, 1986).

Water Markets and Transfers

The "first in time, first in right" appropriation doctrine, which favors the longest standing water rights, governs much of the West's surface water and some groundwater. The appropriation doctrine has the potential to establish clear, transferable property rights to water -- a precondition for effective operation of water markets. The potential for water transfers to the highest value users has not yet been fully realized because the nature and transferability of the rights are obscured by legal and administrative factors (Trelease, 1977; Frederick, 1986; Saliba et al., 1987). Following are some examples:

- Rather than grant absolute ownership, states with prior appropriation rules grant rights to use water for beneficial purposes. Water rights not put to beneficial use may be forfeited. This encourages a use-it-or-lose-it attitude.

- Federal and Native American water rights remain unquantified in some areas such as the Colorado River Basin.

- The emergence in law of the "public trust doctrine," which states that all uses are subject to the public interest, has cast a cloud over some water rights. This has been true in California, where the public interest has driven a reexamination of withdrawals from Mono Lake, and where existing permits have been modified to protect the Sacramento-San Joaquin Delta from saltwater intrusion. Montana is increasingly basing water management plans on its instream flow requirements and is exploring ways to have these requirements for all future beneficial instream uses count as a bona fide use of the Missouri River to slow the growth rate of water diversion for offstream uses (Tarlock, 1987).

- In resolving interstate water disputes, a federal common law of "equitable apportionment" has developed under which an informed judgment, based on consideration of many factors, secures a "just and equitable" water allocation (see Strock, 1987). The Supreme Court decided in Colorado v. New Mexico (456 U.S. 176, 1982) that equitable apportionment may be used to override prior appropriation priorities in cases of major flow reductions. The Supreme Court specifically mentioned climatic conditions in ruling that prior appropriation systems would otherwise protect arguably wasteful and inefficient uses of water at the expense of other uses (see Strock, 1987).

- Because of imperfect competition, third-party effects, uncertainty over administrative rules, and equity considerations, water market prices may not appropriately measure water values according to economic efficiency criteria (Gibbons, 1986; Saliba et al., 1987).

- It is possible to control groundwater withdrawals, but for a number of reasons it is difficult to establish market mechanisms for groundwater allocation. Because all groundwater users essentially draw from a shared pool, groundwater resources are treated as "common property." As a result, property rights are difficult to define, third-party impacts of transfers of groundwater rights are significant, and interstate agreements concerning allocation of interstate aquifer water are difficult to attain (Emel, 1987).

Despite the obstacles, transfer of water rights among users -- especially from irrigators to municipalities and power companies seeking water for urban expansion and electricity production -- is becoming common in many western states (Wahl and Osterhoudt, 1986; Frederick, 1986). Methods include negotiated purchases, short-term exchanges during droughts, and water banks and markets (Wahl and Osterhoudt, 1985; Saliba et al., 1987; Wahl and Davis, 1986).

Legislation in many western states has facilitated water transfers (Frederick, 1986; Frederick and Kneese, 1989). For instance, Arizona's new water law facilitates the purchase of agricultural land for water rights, and the use of that water for urban development. Strict technical standards imposing conservation on municipal and industrial water uses, such as watering golf courses with wastewater, are also part of Arizona's laws (Saliba et al., 1987).

Frederick and Kneese (1989) caution that water transfers occur gradually and are not likely to affect more than a small percentage of agricultural water rights for the foreseeable future. However, legal and institutional changes facilitating water markets and demand for water by high-value users may be accelerated under the stress of climate change (Trelease, 1977).

Drought Management Policies

Integrating drought planning into water resource management may assume greater priority if climate change aggravates water shortages. The Model Water Use Act (Hrezo et al., 1986) advocates that states or water supply authorities integrate drought management and advance planning into their policies by designating a governmental authority for drought response and by adopting mechanisms for automatically implementing and enforcing water-use restrictions. In 1986, only seven states had comprehensive management plans for water shortages (Hrezo et al., 1986). Most states rely on water rights appropriations, emergency conservation programs, and litigation to allocate water during shortages. Improved capabilities in surface hydrology and in water system modeling and monitoring would be required to support broadened drought contingency planning.

Water Quality

Federal and state legislation and regulations for control of instream water quality have had a dramatic effect on reducing conventional water pollutants since the enactment of the 1972 Clean Water Act. The reduced riverflows and lake levels that are possible under altered climate conditions could necessitate more stringent controls on point and nonpoint sources to meet water quality standards. Promotion of nonpolluting products, waste minimization, and agricultural practices that reduce the application of chemicals will also enhance water quality, making more water of suitable quality available for use.

Many states have adopted measures to protect instream water uses. These include reserving flows or granting rights for particular instream uses and directing agencies to review impacts before granting new rights (U.S. Water Resources Council, 1980; Frederick and Kneese, 1989). Regulations limiting water use may have to be modified where climate change has resulted in reduced flows during droughts.

Policies for Floodplains

The National Flood Insurance Program was enacted in 1968, with major amendments in 1973. The program provides subsidized flood insurance for existing structures in flood-prone areas, provided that the community with jurisdiction regulates the location and construction of new buildings to minimize future flood losses. New structures that comply with the restrictions are eligible for insurance at full actuarial rates.

In 1979, the program took in $140 million in premiums and paid $480 million in claims. Recently, the program was authorized to relocate structures exposed to repeated flood or erosion damage rather than pay claims for such structures.

Where rainfall and flooding increase, the 100-year floodplain would expand, and rate maps would need revision. Premium payments and claims would rise.

RESEARCH NEEDS

Water is the principal medium by which changes in atmospheric conditions are transmitted to the environment, the economy, and society. Hydrology is the key discipline that enables us to understand and project these effects. Improvements in both the GCMs and regional hydrologic models are needed so that we may understand the impacts of climate change and devise appropriate water resources management strategies. Specifically, GCMs do not yet provide regional forecasts at the level of certainty and temporal and spatial resolution required for decisionmakers. To be more helpful, the GCMs should provide forecasts specific to individual river basins or demand centers, and should describe hydrologic conditions over the typical design-life of water resource structures.

Research activities should include the following:

- Monitor atmospheric, oceanic, and hydrologic conditions to detect evidence of water resources impacts of climate change.

- Continue to develop and refine regional hydrologic models that are capable of modeling the changes in runoff, water availability, water use, and evapotranspiration induced by changes in temperature and atmospheric conditions. This research should focus on vulnerable river basins where demand approaches or exceeds safe yield or where hydrologic variability is high.

- Refine global climate change models and link them to regional hydrologic models so that regional water resource planners, engineers, and managers can use their projections more confidently.
- Study the sensitivity of existing water systems to possible changes in climate conditions.

At the same time, the following research is needed to identify opportunities for adopting measures to adjust and adapt to climate change.

- Quantify federal and Native American water rights in the West.

- Examine how present institutions and markets can better allocate water among users and provide incentives to conserve water.

- Assess the extent to which laws and regulations may exacerbate the effects of climate change. (Examples include thermal controls for rivers and federal pricing and reallocation policies for irrigation water.)

- Identify, project, and quantify the demographic and institutional adjustments that may occur in the absence of public action in response to climate-induced impacts on water resources. This research will reduce uncertainty for policymakers regarding where concerted public action may be or not be needed.

REFERENCES

Bajwa, S., M. Grosswhite, and J.E. Hostetler. 1987. Agricultural Irrigation and Water Supply. Agriculture Information Bulletin 532. U.S. Department of Agriculture. Washington, DC: U.S. Government Printing Office.

Beran, M. 1986. The water resource impact of future climate change and variability. In: Titus, J., ed. Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 1: Overview. Washington, DC: U.S. Environmental Protection Agency, pp. 299-330.

Breitstein, L., and R.C. Tucker. 1986. Water Reuse and Recycle in the U.S. Steam Electric Generating Industry - An Assessment of Current Practice and Potential for Future Applications. Report to U.S. Geological Survey, Grant No. 14-080001-61074. Bethesda, MD: Dames and Moore.

Butcher, W.R., and N.K. Whittlesey. 1986.

Competition between irrigation and hydropower in the Pacific Northwest. In: Frederick, K.D., ed. Scarce Water and Institutional Change. Washington, DC: Resources for the Future

Dracup, JA. 1977. Impact on the Colorado River Basin and southwest water supply. In: The National Research Council, ed. Climate, Climatic Change, and Water Supply. Washington, DC: National Academy of Sciences, pp. 121- 132.

Emel, J.L. 1987. Groundwater rights: definition and transfer. Natural Resources Journal 27:653-674.

Farber, K.D., and G.L. Rutledge. 1987. Pollution abatement and control expenditure, 1982-85. Survey of Current Business May:21-26.

Frederick, K.D., and J.C. Hansen. 1982. Water for Western Agriculture. Washington, DC: Resources for the Future.

Frederick, K.D. 1986. In: Frederick, K.D., ed. Scarce Water and Institutional Change. Washington, DC: Resources for the Future.

Frederick, K.D., and A.V. Kneese. 1989. Reallocation by markets and prices. In: Waggoner, P.E., ed. Climate Change and U.S. Water Resources. New York: John Wiley and Sons. In press. Gibbons, D.C. 1986. The Economic Value of Water. Washington, DC: Resources for the Future.

Gleick, P.H. 1987. Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases. Climatic Change 10:137-161.

Gleick, P.H. 1989. The sensitivities and vulnerabilities of water supply systems to climatic changes. In: Waggoner, P.E., ed. Climatic Variability, Climate Change, and U.S. Water Resources. New York: press.

Hanchey, J.R., K.E. Schilling, and E.Z. Stakluv. 1988. Water resources planning under climate uncertainty. In: Preparing for Climate Change. Proceedings of the First North American Conference on Preparing for Climate Change. Rockville, MD: Government Institutes, Inc. pp. 394-405.

Hansen, J., A. Lacis, D. Rind, G. Russell, 1. Fung, P. Ashcraft, S. Lebedeff, R. Ruedy, and P. Stone. 1986. The greenhouse effect: projections of global climate change. In: Titus, J., ed. Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 1: Overview. Washington, DC: U.S. Environmental Protection Agency, pp. 199-218.

Harkness, W.E., H.F. Lins, and W.M. Alley. 1985. Drought in the Delaware River Basin. In: National Water Summary. 1985: Hydrologic Events and Surface-Water Resources. Washington, DC: U.S. Geological Survey, U.S. Government Printing Office, pp. 29-40.

Hobbs, B.F., and P.M. Meier. 1979. An analysis of water resources constraints on power plant siting in the Mid- Atlantic States. Water Resources Bulletin 15(6):1666- 1676.

Hrezo, M.S., P.G. Bridgeman, and W.R. Walker. 1986. Integrating drought planning into water resources management. Natural Resources Journal 26:141-167.

Jacoby, H.D. 1989. Water Quality. In: Waggoner, P.E., ed. Climate Change and U.S. Water Resources. New York: John Wiley and Sons. In press. John Wiley and Sons. In Water Resources. New York: John Wiley and Sons. In press.

Kaplan, E., M. Rubino, and D. Neuhaus. 1981. Water Resource Development and Energy Growth in the Northeast. Brookhaven, NY: Brookhaven National Laboratory, Report BNL 51522.

Klemes, V., and J. Nemec. 1985. Assessing the impact of climate change on the development of surface water resources. In: Klemes V., ed. Sensitivity of Water Resource Systems to Climate Variations. Geneva: World Meteorological Office.

Kneese, A.V., and G. Bonem. 1986. Hypothetical shocks to water allocation institutions in the Colorado Basin. In: Weatherford, G., and F.L. Rosenberg, NJ. 1988. Global climate change holds Brown, eds. New Courses for the Colorado River: problems and uncertainties for agriculture. In: Major Issues for the Next Century. Albuquerque: Tutwiler, M.A., ed. U.S. Agriculture in a Global University of New Mexico Press, pp. 87-108.

Langbein, W.B. et al. 1949. Annual runoff in the United States. Geological Survey Circular 5. Washington, DC:

U.S. Department of the Interior.

Linsley, R.K., and J.B. Franzini. 1979. Water Resources Engineering. New York: McGraw-Hill, Inc.

Matalas, N.C., and M.B. Fiering. 1977. Water-resource systems planning. In: The National Research Council, ed. Climate, Climatic Change, and Water Supply. Washington, DC: National Academy of Sciences, pp. 99-110.

National Council on Public Works Improvement. 1988. Fragile Foundations: A Report on America's Public Works. Final Report to the President and to the Congress. Washington, DC: U.S. Government Printing Office.

National Research Council. 1977. Climate, Climatic Change, and Water Supply. Washington, DC: National Academy Press.

National Research Council. 1988. Estimating Probabilities of Extreme Floods. National Research Council, Committee on Techniques for Estimating Probabilities of Extreme Floods, Water Science and Technology Board; and Commission on Physical Sciences, Mathematics, and Resources. Washington, DC: National Academy Press.

Nemec, J., and J.C. Schaake. 1982. Sensitivity of water resource systems to climate variation. Hydrological Sciences Journal 27:327-43.

Revelle, R.R., and P.E. Waggoner. 1983. Effects of the carbon dioxide induced climatic change on water supplies in the western United States. In: Changing Climate: Report of the Carbon Dioxide Assessment Committee. Washington, DC: National Academy Press.

Rind, D., and S. Lebedeff. 1984. Potential Climatic Impacts of Increasing Atmosphere CO_2 With Emphasis on Water Availability and Hydrology in the United States. Washington, DC: U.S. Environmental Protection Agency.

Rosenberg, N.J. 1988. Global climate change holds problems and uncertainties for agriculture. In: Tutwiler, M.A., ed. U.S. Agriculture in a Global Setting. Washington, DC: Resources for the Future.

Saliba, B.C., D.B. Bush, W.E. Martinard, and T.C. Brown. 1987. Do water market prices appropriately measure water values? Natural Resources Journal 27:617-652.

Schwarz, H.E. 1977. Climatic change and water supply: how sensitive is the Northeast? In: National Research Council, ed. Climate, Climatic Change, and Water Supply. Washington, DC: National Academy of Sciences, pp. 111-120.

Sheer, D.P. 1985. Managing water supplies to increase water availability. In: National Water Summary. Hydrologic Events and
Surface-Water Resources. Washington, DC: U.S. Geological Survey, U.S. Government Printing Office, pp. 101-112.

Solley, W.B., C.F. Merck, and R.R. Pierce. 1988. Estimated use of water in the United States in 1985. U.S. Geological Survey. Circular 1004. Washington, DC: U.S. Government Printing Office.

Stockton, C.W., and W.R. Boggess. 1979. GeohydrologicalImpBcations of Climate Change on Water Resource Development. Fort Belvoir, VA: U.S. Army Coastal Engineering Research Center.

Strock, J.M. 1987. Adjusting water allocation law to meet water quality and availability concerns in a warming world. In: Preparing for Climate Change. Proceedings of the First North American Conference on Preparing for Climate Change. Rockville, MD: Government Institutes, Inc., pp. 382-387.

Tarlock, A.D. 1987. Damning the dams and ditches: a review of D. Worster, rivers of empire: water aridity and the American West. Natural Resources Journal 27:477-490.

Trelease, FJ. 1977. Climatic change and water law. In: National Research Council, ed. Climate, Climatic Change, and Water Supply. Washington, DC: National Academy of Sciences, pp. 70-84.

U.S. Army Corps of Engineers. 1977. Northeastern United States Water Supply Study, Summary Report. U.S. Army Corps of Engineers, North Atlantic Division.

U.S. Army Corps of Engineers. 1988. Lessons Learned From the 1986 Drought. U.S. Army Corps of

Engineers, Institute for Water Resources. IWR Policy Study 88 - PS - 1. Fort Belvoir, VA

U.S. Congress. 1987. U.S. Congress, Congressional Budget Office. Financing Municipal Water Supply Systems; May.
Washington, DC: Congressional Budget Office.

U.S. Congress. 1984. U.S. Congress, Office of Technology Assessment. Protecting the Nation's Groundwater From
Contamination. Volume 1. Washington, DC: U.S. Government Printing Office.

U.S. Department of the Interior. 1987. U.S. Department of the Interior, Bureau of Reclamation. Assessment '87...A New
Direction for the Bureau of Reclamation. Washington, DC: U.S. Department of the Interior.

U.S. EPA. 1987a. U.S. Environmental Protection Agency. 1986 Needs Survey Report to Congress: Assessment of Needed Publicly Owned Wastewater Treatment Facilities in the United States. EPA430/9-87-001. Washington, DC: U.S. Environmental Protection Agency.

U.S. EPA. 1987b. U.S. Environmental Protection Agency. National Water Quality Inventory: 1986 Report to Congress. EPA- 440/4-87-008. Washington, DC: U.S. Environmental Protection Agency.

U.S. Geological Survey. 1984. National Water Summary 1983 - Hydrological Events and Issues. Water Supply Paper 2250. Washington, DC: U.S. Government Printing Office.

U.S. Geological Survey. 1985. National Water Summary 1984. Water Supply Paper 2275. Washington, DC: U.S. Government Printing Office.

U.S. Geological Survey. 1986. National Water Summary 1984. Water Supply Paper 2300. Washington, DC: U.S. Government Printing Office.

U.S. Water Resources Council. 1980. State of the States: Water Resources Planning and Management. Washington, DC: U.S. Water Resources Council.

U.S. Water Resources Council. 1978. The Nation's Water Resources 1975-2000: Second National Water Assessment. Vol. 1: Summary. Washington, DC: U.S. Government Printing Office.

Viessman Jr., W., and C. DeMoncada. 1980. State and National Water Use Trends to the Year 2000. Washington, DC:
Congressional Research Service, The Library of Congress.

Wahl, R.W., and R.K. Davis. 1986. Satisfying Southern California's thirst for water: efficient alternatives. In: Frederick, K.D., ed. Scarce Water and Institutional Change. Washington, DC: Resources for the Future.

Wahl, R.W., and F.H. Osterhoudt. 1985. Voluntary transfers of water in the West. In: U.S. Geological Survey. National Water Summary 1985. Hydrologic Events and Surface-Water Resources. Washington, DC: U.S. Government Printing Office, pp. 113- 124.

CHAPTER 1O
ELECTRICITY DEMAND

FINDINGS

Global warming would increase electricity demand, generating capacity requirements, annual generation, and fuel costs nationally. The impacts could be significant within a few decades and would increase substantially over time if global warming continues.

- The new generating capacity requirements induced by climate change effects on electricity demand estimated for 2010 show an increase of 25 to 55 gigawatts (GW), or 9 to 19% above estimated new capacity requirements assuming no change in climate. Between 2010 and 2055, climate change impacts on electricity demand could accelerate, increasing new capacity requirements by 200 to 400 GW (14 to 23%) above what would be needed in the absence of climate change. These capacity increases would require investments of approximately $200 to $300 billion (in 1986 dollars). In the absence of climate change, population and economic growth may require investments of approximately $2.4 to 3.3 trillion through 2055.

- Estimated increases in annual electricity generation and fuel use induced by climate change represent several thousand gigawatthours by 2055. The estimated increases are 1 to 2% in 2010 and 4 to 6% in 2055. Annual fuel, operation, and maintenance cost to meet increased electricity demand would be several hundred million dollars in 2010 and several billion dollars in 2055. Without climate change, these annual costs would be $475 to 655 billion in 2055.

- Estimated regional impacts differ substantially. The largest increases could occur in the Southeast and Southwest, where air-conditioning demands are large relative to heating. Northern border states may have a net reduction in electricity generation relative to base case requirements assuming no change in climate. These changes could be exacerbated by reductions in hydropower production and increases in demand for electricity to run irrigation equipment.

- These results are sensitive to assumptions about the rates of economic growth, technological improvements, and the relationship between electricity use and climate. The potential savings in other energy sources (gas and oil) used for space heating and other end uses sensitive to climate and the potentially significant impacts on hydroelectric supplies and other utility operations were not analyzed.

Policy Implications

- Utility executives and planners should begin to consider climate change as a factor in planning new capacity and future operations. The estimated impacts of climate change in some regions are similar to the range of other uncertainties and issues utility planners need to consider over the 20- to 30-year period. Additional climate and utility analyses are needed to develop refined risk assessments and risk management strategies.

- The increased demand for electricity induced by climate change also could exacerbate other environmental problems, such as the implementation of "acid rain" strategies, adherence to the international nitrogen oxide treaty, state implementation plans for ozone control, and thermal pollution control permit requirements. The Environmental Protection Agency should analyze the impacts of climate change on long-range policies and should include climate change as an explicit criterion in making risk management decisions when appropriate.

- The increased demand for electricity could make policies to stabilize the atmosphere through energy conservation more difficult to achieve. The estimated increases in electricity generation induced by climate change could increase annual CO_2 emissions, depending upon future utility technology and fuel choice decisions. Assuming no change in efficiency of energy production and demand, reliance on coal-based technologies to meet the increased demands could increase CO_2 emissions by 40 to 65 million tons in 2010 and by 250 to 500 million tons in 2055. Use of other, lower CO_2 emitting technologies and fuels (e.g., efficient conversion technologies and nuclear and renewable resources) would reduce these incremental additions. In addition, warmer winter temperatures could reduce the demand for oil and gas in end uses such as residential furnaces for heating, thereby lowering CO_2 emissions from these sources. Future analyses of national and international strategies to limit greenhouse gases should include the changes in energy demand created by global warming as a positive feedback.

CLIMATE CHANGE AND ELECTRICITY DEMAND

Climate change could affect a wide range of energy sources and uses. In the near term, policies aimed at reducing emissions of greenhouse gases from fossil fuel combustion could affect the level and mix of fuel consumption in various end-use technologies and in the generation of electric power. In the longer term, changes in temperature, precipitation, and other climatic conditions also could affect energy resources. For example, warmer temperatures likely would reduce the demand for fuels used in the winter for space heating and increase the demand for fuels used in the summer for air-conditioning; and reduced precipitation and soil moisture in some regions could increase the use of energy to pump water for irrigation. These effects could be particularly significant for planning in the electric utility industry based upon the substantial amount of electric load accounted for by weather-sensitive end uses, the variety of resources used to generate electric power, and the capital-intensivity of the industry. One major consideration is the potential impact of climate change on the demand for electricity and the implications of changes in demand on utility capacity and generation requirements.

Many electrical end uses vary with weather conditions. The principal weather-sensitive end uses are space heating, cooling, and irrigation pumping and -- to a lesser degree -- water heating, cooking, and refrigeration. These applications 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.

Changes in weather-sensitive demands for electricity can affect both the amount and the characteristics of generating capacity that a utility must build and maintain to ensure reliable service. These changes also can affect fuel requirements and the characteristics of efficient utility system operations, particularly the scheduling and dispatching of the utility's generating capacity. For example, electric energy used for air-conditioning exceeds that used for space heating nationwide, and the temperature sensitivity associated with cooling is higher than that associated with heating. This implies not only changes in seasonal electricity demands but also increases in annual electricity demands as a result of higher temperatures.

Similarly, utilities in most regions experience their peak demands in the summer. A rise in air conditioning and other temperature-sensitive summer loads would significantly increase peak loads and, as a result, would step up utility investments in new generating capacity needed to meet additional demands and to maintain system reliability.

Examples of other ways in which climate could affect electric utilities include the following. Changes in precipitation, evaporation, and runoff from mountain snowpack as well as changes in water management practices in response to climate change could affect the annual and seasonal availability of streamflow to generate hydropower. Reductions in hydropower would require utilities to rely upon other, possibly more costly and less environmentally benign generation sources to meet customer needs. Furthermore, reductions in water resources would adversely affect the availability and/or cost of water for powerplant cooling.

Other direct impacts of climate change on electric utilities include the effects of temperatures on powerplant operating efficiencies, the effects of sea level rise on the protection and siting of coastal facilities, and the effects of changes in various climate conditions on the supply of renewable energy resources such as solar and wind power. Also, legislation and regulations designed to limit greenhouse gas emissions from utility sources could significantly affect the supply and cost of electricity generation.

Although some of these impacts could significantly affect utility planning and operations (particularly on a regional basis), they have not been analyzed in detail and are not addressed in this report. Further research and analysis are needed to develop a more complete assessment of utility impacts.

PREVIOUS CLIMATE CHANGE STUDIES

A number of utilities conduct analyses relating short-term variations in weather conditions with a need to "weather-normalize" historical demand data and to test the sensitivity of system reliability and operations to these short-term variations. Furthermore, some researchers have speculated regarding the potential effects of longer term climate changes on electricity demand (e.g., Stokoe et al., 1987).

However, only one previous study has estimated the potential implications of longer term, global warming-associated temperature changes on electricity demands and the effects of changes in demand on utility investment and operating plans. Linder et al. (1987) used general circulation model (GCM) results to estimate the potential impacts of temperature change on electricity demand (and on the supply of hydropower) for selected case study utility systems in two geographical areas: a utility located in the southeastern United States and the major utilities in New York State, disaggregated into upstate and downstate systems.

Linder et al. found that temperature increase could significantly heighten annual and peak electricity demands by 2015, and that a temperature rise would require construction of new generating capacity and increases in annual generation. The southeastern utility had higher estimated increases in electricity demand, generation, and production costs than the New York utilities because of greater electricity demands for air-conditioning. In addition, streamflow used to generate hydropower in New York could be reduced, requiring increased use of fossil fuel generation to meet customer demands for electricity.

CLIMATE CHANGE STUDY IN THIS REPORT

Study Design

Linder and Inglis (Volume H) expanded the case studies (Linder et al., 1987) of the sensitivity of electricity demand to climate change and conducted a national analysis of electricity demand. Relevant regional results from the national studies of Linder and Inglis are discussed in the regional chapters of this report.

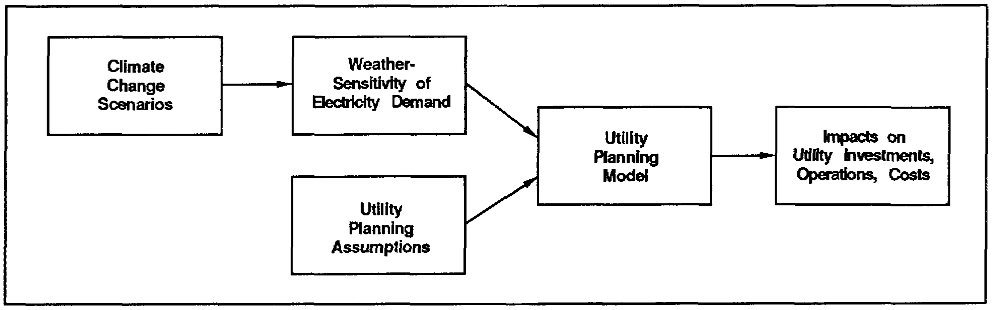


Figure 10-1. Analytic approach (Linder and Inglis, Volume H).

The analytic approach developed by Linder et al. (1987) formed the basis for estimating the regional and national impacts described in this report. The principal steps in the approach are summarized in Figure 10-1(see Volume H for more details). Estimated impacts were developed for the relatively near term (from the present to 2010, within electric utility long-range resource planning horizons of 20 to 30 years) and over the longer term (to 2055), when the magnitude of temperature changes is expected to approach equilibrium levels representative of a doubling of atmospheric concentrations of CO . Linder and Inglis used Goddard Institute for pace Studies (GISS) A and B transient estimates of temperature change in 2010 and GISS A estimates for 2055 in their calculations. The scenario changes in annual temperatures for the United States range from about 1.0 to 1.4 C in 2010 and are approximately 3.7 C by 2055. Regional temperature scenarios show greater variation.

Linder and Inglis used actual utility demand and temperature data from the case study utilities, and from five other large, geographically dispersed utility systems, to develop a set of weather-sensitivity parameters for utility areas. On a weighted-average basis (weighted by electricity sales), utility peak demands were estimated to increase by about 3.1% per change in degree Celsius (ranging from -1.35 to 5.40% across utility areas), and annual energy demands were estimated to increase by about 1.0% per change in degree Celsius (ranging from -0.54 to 2.70%).

A number of uncertainties associated with the data and assumptions used to develop these weather-sensitivity relationships suggested that the relationships may understate customer response to climate change, particularly at higher temperature change levels occurring in the future. For example, the approach did not explicitly account for probable increases in the market saturation of air conditioning equipment as temperatures rise over time. To address this possibility, an alternative case was designed in which the estimated weather sensitivity values were increased by 50%. This was designated as the "higher sensitivity" case.

Since this study is focused on estimating how climate change may affect key utility planning factors, Linder and Inglis used a planning scenario assuming no change in climate (a "base case") to serve as a basis for comparison with planning scenarios under alternative assumptions of climate change for 2010 and 2055. Thus, base case utility plans were developed for 2010 and 2055, using assumptions regarding future demands for electricity in the absence of climate change (reflecting population and economic growth), generating technology option performance and costs, fuel costs, and other utility characteristics. [1]Linder and Inglis assumed that future capacity and generation requirements will be met by investments either in new coal-fired baseload capacity or in oil- and natural gas-fired peaking capacity. Other sources, such as nuclear energy and renewables or innovative fossil fuel-fired technologies (e.g., fluidized bed combustion), were not considered (for further details, see Linder et al., 1987).

Demands for electricity in the absence of climate change can be related to the overall level of economic activity as represented by the gross national product (GNP). Because economic growth assumptions are critical to estimates of future electricity demands, alternative GNP growth rates were assumed in developing the base cases; these ranged from 1.2 to 2.1% per year.[2] These alternative assumptions are referred to as "lower growth" and "higher growth," respectively.

These assumptions served as inputs to a regional planning model called the Coal and Electric Utilities Model (CEUM). CEUM outputs include the amount and characteristics of new generating capacity additions, electricity generation by fuel type, and electricity production costs.

Limitations

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[1] Note that the development and use of a base case reflecting changes in non-climate-related conditions over time was undertaken only for the electricity demand study, not for other areas in the report. Changes in population and technology are considered in Chapter 6: Agriculture.

[2] These GNP growth rates are relatively conservative, but they are comparable with GNP growth rates used by EPA in its report to Congress on Policy Options for Stabilizing Global Climate.

The study extrapolated temperature-sensitivity findings for some regions and did not include specific analyses of temperature sensitivity for all utility regions of the United States. It focused narrowly on impact pathways, considering only the potential effects of temperature change on changes in electricity demand. Neither the potentially significant impacts of climate change on hydropower availability nor the impacts of reduced water supplies for powerplant cooling were included.

Furthermore, the study did not evaluate the sensitivity of the results to different, doubled-CO_2 GCM climate scenarios (GFDL and OSU), although the use of the GISS transient experiment results for 2010 and 2055 indicates relative sensitivities to small and large temperature changes.

The study did not consider variations in temperature changes and the occurrence of extreme events, which affect powerplant dispatch and determinations of peak demands, respectively, and are important for utility planning.

Many uncertainties exist regarding the concepts, methods, and assumptions involved in developing and applying estimates of the temperature sensitivity of demand. For example, a key assumption is that the estimated sensitivities of demand to historical, short-term variations in temperature are adequate representations of future relationships between electricity demand and long-term changes in mean temperatures.

Uncertainties also exist regarding market, regulatory, technological, and other conditions that will face the utility industry in the future. For example, technological changes that improve the energy efficiency of weather-sensitive end-use equipment or electricity-generating equipment will continue to evolve. These changes would likely lead to lower climate change impacts than estimated in this report. On the other hand, regulatory changes aimed at reducing the emissions of greenhouse gases from electricity generation could limit a utility's future fuel and technology investment options, leading to higher estimates of cost impacts than reported here. Because of these limitations, it is important to recall that the results presented in the next section should not be considered as projections of actual powerplant investments and utility operations, but rather as comparisons providing estimates of the magnitude of sensitivities to alternative climate change assumptions.

Results

The potential national impacts for 2010 and 2055 are summarized in Table 10-1. The table presents base case values (i.e., assuming no change in climate) for each year and estimated impacts represented by changes from the base case values. The impacts for 2055 are presented for both the lower growth GNP and the higher growth GNP cases. Also, where ranges of impacts are presented, they summarize the estimates under alternative climate change scenarios (GISS A and GISS B) and assumptions of the weather sensitivity of demand ("estimated sensitivity" and "higher sensitivity").

Estimated increases in peak demand over the base case on a national basis range from 2 to 6% by 2010. Changes in estimated annual energy requirements by 2010 are more modest, ranging from 1 to 2%. In 2055, peak national demands are estimated to increase by 13 to 20% above base case values, and annual energy requirements are estimated to increase by 4 to 6%.

By 2010, new climate change-induced generating capacity requirements increase by 6 to 19%, or about 24 to 55 GW, representing an average increase of up to 1 GW per state (approximately the capacity of one to two large nuclear or coal-fired baseload powerplants). The majority of the capacity increase is for peaking capacity rather than baseload capacity. The investment associated with these capacity increases is several billion dollars (in constant 1986 dollars). By 2055, the change in new capacity requirements increases in percentage terms and represents several hundred GW. Under high GNP and higher weather-sensitivity assumptions, the estimated increase attributable to climate change is almost 400 GW, or 23%. To put these results into perspective, it should be noted that current generating capacity in the United States is about 700 GW. The increase in new capacity requirements under the base case is 1,350 to 1,780 GW.

Annual generation increases for the United States are not as large in percentage terms as those estimated for new generating capacity requirements, but

Table 10-1. The Potential National Impacts of Climate Change on Electric Utilities

	2010		2055			
			Lower GNP		Higher GNP	
	Base	Increase	Base	Increase	Base	Increase
Peak Demand (GW)	774	20-44	1,355	181	1,780	238-357
New capacity requirements (GW)[a]						
Peaking	50	13-33	176	118	254	182-286
Baseload	226	11-22	1,011	67	1,423	74-98
Total	276	24-55	1,187	185	1,677	227-384
Annual sales (bkWh)	3,847	39-67	6,732	281	8,848	370-555
Annual generation[b] (bkWh)						
Oil/gas	287	(12)-(29)	221	2	308	27-51
Coal	2,798	54-103	6,242	305	8,295	381-560
Other	1,092	1-(1)	846	(2)	1,003	(7)-0
Total	4,177	43-72	7,309	305	9,607	401-611
Cumulative capital costs[c,d]	669	25-48	1,765	173	2,650	222-328
Annual costs[d]	162	3-6	474	33	655	48-73

[a] Includes reserve margin requirements; does not include “firm scheduled” capacity.
[b] Includes transmission and distribution losses.
[c] “Base” values include regional capital expenditures for utility-related equipment in addition to new generating capacity (e.g., new transmission facilities).
[d] In billions of 1986 dollars.
Abbreviations: GW = gigawatts; bkWh = billion killowatthours.
Source: Linder and Inglis (Volume H).

nonetheless, they account for several hundred billion kWh by 2055. In the near term (i.e., to 2010), increased levels and changing patterns of climate change-induced electricity demand permit utilities in some areas having excess generating capacity to serve the growing needs of utilities in other areas through substitution of lower cost baseload generation for higher cost peaking generation. On net, peaking generation would be lower as a result of climate change in 2010(see Linder et al., 1987, for further detail). In 2055, peaking generation is projected to increase along with baseload generation, because all the excess capacity that had existed in 2010 either would have been fully used by growing demands to 2055 or would have been retired. The estimated impacts of climate change on national new generating capacity requirements and annual generation are illustrated in Figure 10-2.

Table 10-1 also indicates that the increase in annual costs for capital, fuel, and operation and maintenance associated with climate change-induced modifications in utility investments and operations are a few billion dollars in 2010 and are $33 to $73 billion by 2055, a 7 to 15% increase over base case values of $475 to $655 billion for 2055.

Figures 10-3 and 10-4 illustrate the diversity of the estimated results for generating capacity on a state-by-state basis. The state and regional differences reflect differences in current climate conditions (e.g., seasonal temperature patterns), assumed future climate changes, and electricity enduse and utility system characteristics (e.g., market saturation of weather-sensitive appliances and equipment).

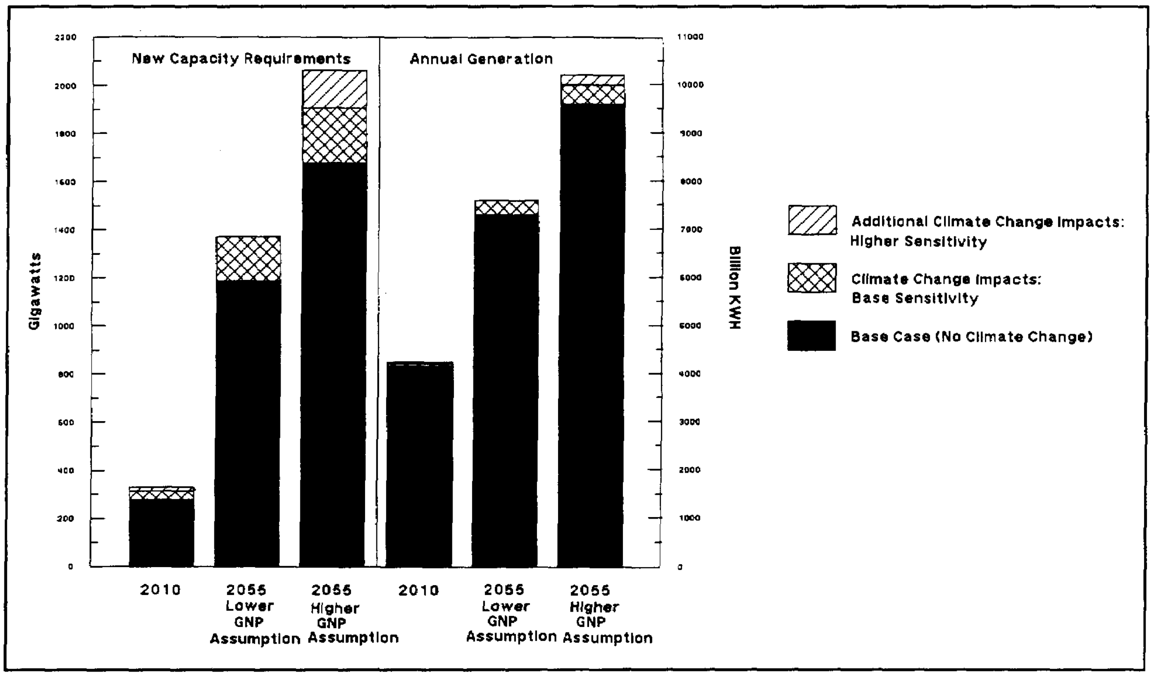

Figure 10-2. Potential impacts of climate change on electric utilities, United States (Linder and Inglis, Volume H).

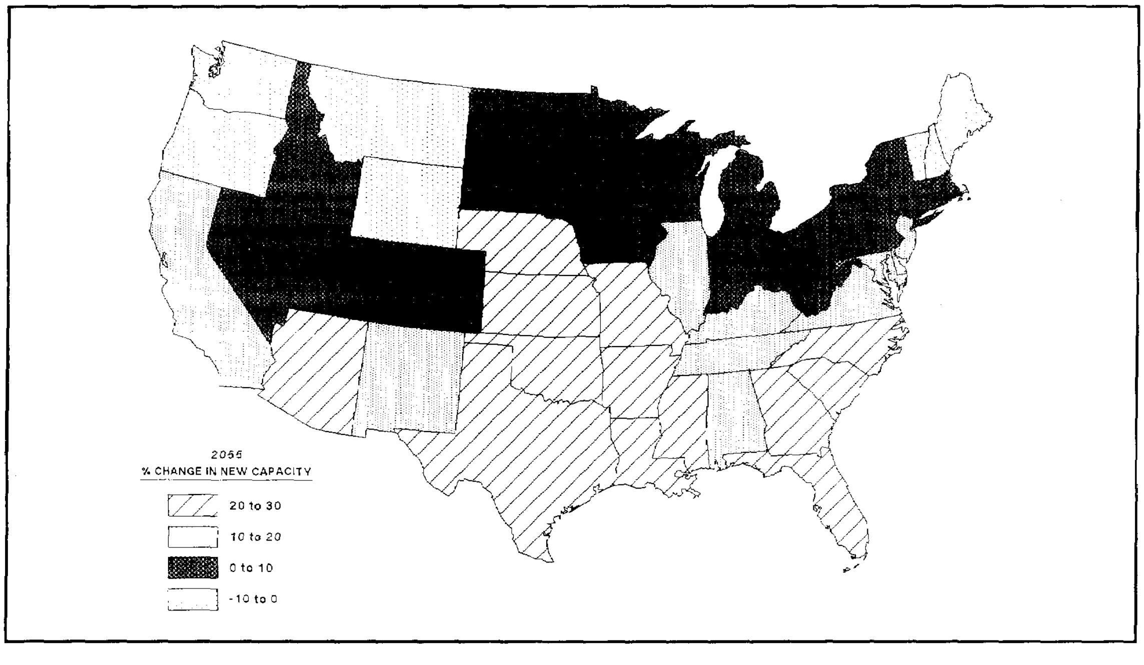

Figure 10-3. Changes in electric utility capacity additions by state, induced by climate change in 2055 (derived from Linder and Inglis, Volume H).

Figure 10-3 shows that estimated reductions in new capacity requirements induced by climate change are limited to the winter-peaking regions of the extreme Northeast and Northwest. The Great Lakes, northern Great Plains, and Mountain States are estimated to experience increased new capacity requirements by 2055 in the range of 0 to 10%. Increases greater than 20% are concentrated in the Southeast, southern Great Plains, and Southwest.

Figure 10-4 shows a somewhat similar geographic pattern of impacts for electricity generation in 2055. Reductions in generation are estimated in the North, and the greatest increases are concentrated in the Southwest. Despite substantial use of air-conditioning in the Southeast, the estimated increases in generation are only in the 5 to 10% range. There is a relatively high market saturation of electric heat in the region, and the increase in cooling is partly offset by a decrease in heating as a result of warmer winters.

Because regions are affected differently, the results indicate potential changes in the patterns of interregional bulk power exchanges and capacity sales over time and as climate changes. For example, under the assumption of increasing temperatures, some regions may require significant amounts of additional generating capacity to reliably meet increased demands during peak (cooling) seasons, but may experience lower demands in other (heating) seasons. As a result, the region's needs may be for powerplants that are utilized heavily during only part of the year. Low annual utilization in the region would not justify construction of highcapital and low-fuel cost baseload powerplants that can produce electricity more cheaply (per kWh) than low-capital and high-fuel-cost peaking units. However, when considered across several regions, the least-cost plan may be to construct baseload powerplants in certain regions, utilize them to an extent greater than required by the region, and sell the "excess" electricity from these plants into other regions. The location and amount of these interregional sales would be subject to the transfer capabilities of transmission capacity in place. An alternative to increased interregional bulk power sales would be the development and application of efficient and effective energy storage technologies.

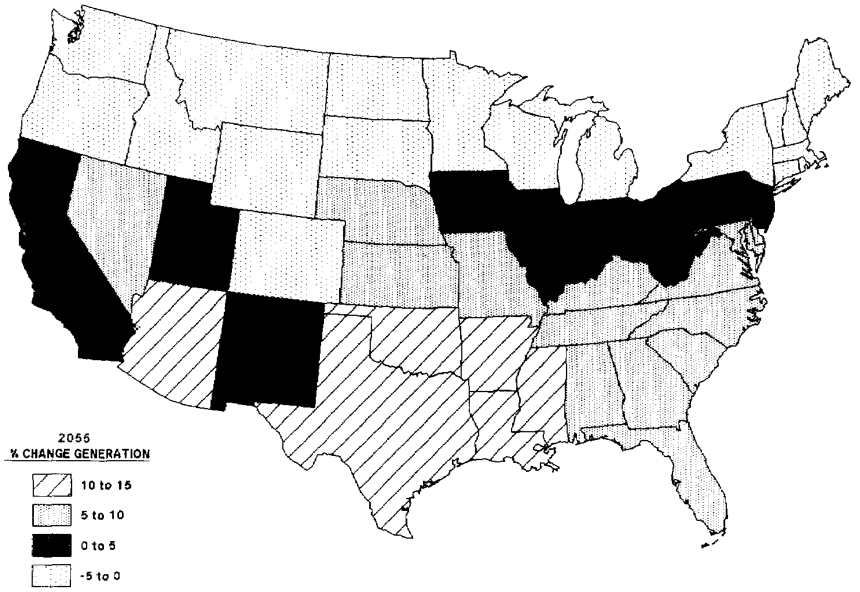

Figure 10-4. Changes in electricity generation by state, induced by climate change in 2055 (derived from Linder and Inglis, Volume H).

SOCIOECONOMIC AND ENVIRONMENTAL IMPLICATIONS

Despite the limitations of the analysis and the need for more research to refine the data and methods used, the results are judged to be reasonable estimates of the sensitivity of electricity demand to potential climate change. Key socioeconomic and environmental implications of the results stem from the increases in electric generating capacity and generation requirements associated with climate-induced changes in demand. The implications include the following:

- Climate change could result in overall fuel mixes for electricity generation that differ from those expected in the absence of climate change.
- Climate change would not evenly affect regional demands for electricity. Greater impacts would occur in regions where weather-sensitive end uses (particularly airconditioning) are important sources of electricity demand. Substantially greater climate change impacts were estimated for the Southeast and Southwest than for other regions, especially the northern tier of states. Other impacts not addressed in this study, such as the availability of water for hydropower generation and powerplant cooling, also would be more important in some regions (e.g., the West) than in others.
- Regional differences in capacity and generation requirements suggest that important new opportunities for interregional bulk power exchanges or capacity sales may arise as a result of climate change.
- The impacts of uncertain climate conditions over the long term could pose significant planning and economic risks. Because of long lead times required to plan and build economic baseload generating capacity, the ability of utility planners to correctly anticipate climate change could result in lower electricity production costs. The magnitude of these risks in some regions (e.g., the Southeast and the southern Great Plains) could be similar to other uncertainties that utility planners and decisionmakers must face.
- If the result is confirmed that the majority of new capacity requirements in response to climate change are for peaking capacity, a new technological and market focus would be directed toward this type of generating plant. Related to this would be increased research and development on electricity storage technologies, which would allow lower cost, more efficient powerplants to generate, at off-peak times, electricity for use during peak periods.
- Because increases in customer demands for electricity may be particularly concentrated in certain seasons and at peak periods, conservation and especially load management programs that improve the efficiency or change the patterns of customer uses of electricity could be more cost-effective when considered in the context of potential changes in climate.
- Increased electricity generation implies the potential for increased adverse environmental impacts depending upon generating technology and fuel-use assumptions. Potential adverse impacts compared with the base case are associated with the following:

  – air quality (e.g., emissions of sulfur dioxide, NOW and other pollutants);
  – land use for new powerplant sites, fuel extraction, fuel storage, and solid waste disposal;
  – water quality and use (e.g., for powerplant cooling and fuel processing); and
  – resource depletion, especially of nonrenewable fuels such as natural gas.

  Of particular concern would be additional water withdrawal and consumption requirements in areas where water supplies may be reduced by climate change.[3]

- Increased electricity generation also implies increased emissions of CO. and other greenhouse gases compared with base case emissions. For example, if the estimated increases in climate change-induced generation reported in Table 10-1 were met by conventional technologies, CO_2 emissions could increase by 40 to 65 million tons per year by 2010 and by 250 to 500 million tons per year by 2055.[4] Use of lower CO_2-emitting technologies and fuels -- such as efficient conversion technologies and nuclear or renewable resources -would lower these estimated impacts.

POLICY IMPLICATIONS

In general, the study results suggest that utility planners and policymakers should begin now to assess more fully and to consider climate change as a factor affecting their planning analyses and decisions. If more complete and more detailed analyses support the socioeconomic and environmental implications of the climate change effects described above, they should be explicitly addressed in planning analyses and decisions. Specific policy implications related to the findings include the following:

- In formulating future National Energy Plans, the Department of Energy may wish to consider the potential impacts of climate change on utility demands.

- The interactions of climate change and the current efforts of the Federal Energy Regulatory Commission (FERC) to restructure the electric utility industry are difficult to assess. For example, the industry's response to FERC policies could either accelerate or reduce the rate of emissions of greenhouse gases, depending upon changes in the mix of generating fuels and effects on the efficiency of electricity production. The possible alternative responses should be assessed, and FERC policies should be considered with respect to their potential implications related to climate change issues.

- Increases in electricity demands induced by climate change will make achievement of energy conservation goals more difficult. For example, the conference statement from "The Changing Atmosphere: Implications for Global Strategy" (Environment Canada, 1988) calls for reductions in CO_2 emissions to be achieved in part through increased efforts in energy efficiency and other conservation measures. An initial goal for wealthy, industrialized nations set by the conference is a reduction in CO_2 emissions through conservation of approximately 10% of 1988 emissions levels by 2005. The impacts of climate change to increase electricity demand should be factored into the policies and plans designed to achieve this conservation goal.

- Similarly, climate change impacts may exacerbate the difficulties or costs associated with implementing acid rain mitigation strategies being considered by the Congress. However, these strategies center primarily on near-term solutions focusing on emissions reductions from existing powerplants, and the impacts of climate change may not be large within that time frame.

- Although not addressed directly in the analyses underlying this report, state and federal agencies should consider mitigation strategies that include energy conservation; increased efficiency in the production, conversion, and use of energy; and the development and reliance on fuel sources with

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[3] For example, increased electricity generation induced by climate change in northern California could increase requirements for water withdrawal by 600 to 1,200 million cubic feet and for water consumption by 200 to 400 million cubic feet in 2055. Comparable figures for the southern Great Plains in 2055 would be water withdrawal of 5,800 to 11,500 million cubic feet and consumption of 1,800 to 3,500 million cubic feet.

[4] Note, however, that these increases in emissions from electricity production could be offset, at least in part, by reduced demand for space heating provided by natural gas and oil furnaces or by other direct uses of fossil fuels.

low CO_2 emissions.

RESEARCH NEEDS

Important areas for further climate change research include improved methods for developing and disseminating climate change scenarios, with particular emphasis on (1) improved estimates of climate variables (in addition to temperature) relevant to utility impact assessment (e.g., hydrologic factors, winds); (2) estimates of the possible impacts of global warming on variations in weather conditions and the occurrence of extreme events; (3) continued attention to estimates of the rate of climate change over time; and (4) estimates of climate change at a more disaggregated regional or local level.

Follow-on research suggestions on the utility side include (1) refinement of the analytical approach, in part through lessons learned from additional utility-specific analyses; (2) more detailed and complete analyses of the weather sensitivity of customer demand for electricity; (3) extension of the approach to consider other pathways (including indirect and secondary effects) through which climate change could affect utility investments and operations; and (4) an assessment of the value of improved climate change information to utility planners and managers.

REFERENCES

Environment Canada. 1988. The Changing Atmosphere: Implications for Global Security Conference Statement. Environment Canada, Government of Canada. Toronto; June 27-30.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. ICF Incorporated. 1987. Potential Impacts of Climate Change on Electric Utilities. Report 88-2. Albany, New York: New York State Energy Research and Development Authority. (Note: This report was also published by the Electric Power Research Institute, Palo Alto, California, in January 1989; report no. EN-6249.)

Stokoe, P.K., and M. LeBlanc. P. Lane and Associates, Ltd., and Discovery Consultants, Ltd. 1987. Socio-economic Assessment of the Physical and Ecological Impacts of Climate Change on the Marine Environment of the Atlantic Region of Canada, Phase 1. Halifax, Nova Scotia, Canada: School for Resource and Environmental Studies, Dalhousie University.

CHAPTER 11
AIR QUALITY

FINDINGS

- Potential changes in regional temperatures, precipitation patterns, clouds, windspeed and direction, and atmospheric water vapor that will accompany global climate change will affect future air pollution levels and episodes in the United States.

- While uncertainties remain, it is likely that an increase in global temperatures would have the following effects on air quality, if other variables remain constant. These potential impacts should be interpreted as relative changes as compared with air quality levels without climate change. This chapter does not predict what will happen to air quality without climate change and does not consider changes in anthropogenic emissions or technology.

  – Ozone levels in many urban areas would increase because higher global temperatures would speed the reaction rates producing ozone in the atmosphere.

  – Natural emissions of hydrocarbons would increase with a temperature rise. Natural emissions of sulfur would also change, but the direction is uncertain. The hydrocarbons and nitrogen oxides participate in reactions that produce ozone.

  – Manmade emissions of hydrocarbons, nitrogen oxides, and sulfur oxides may rise if more fossil fuel is used to meet higher electricity needs (see Chapter 10: Electricity Demand) and if technology does not improve.

  – The formation of acidic materials (such as sulfates) would increase with warmer temperatures because sulfur and nitrogen oxides would oxidize more rapidly. The ultimate effect on acid deposition is difficult to assess because of changes in clouds, winds, and precipitation.

  – Visibility may decrease because of the increase in hydrocarbon emissions and the rate at which sulfur dioxide is oxidized to sulfate.

  – The small increase in temperature will not significantly affect carbon monoxide emissions.

- Preliminary analyses of the effects of a scenario of a 4 C temperature increase in the San Francisco Bay area, with no change in emissions or other climate variables, on ozone concentrations suggest that maximum ozone concentrations could increase by approximately 20%, that the area in which the National Ambient Air Quality Standard (NAAQS) would be exceeded would almost double, and that the number of people-hours of exposure would triple. The Midwest and Southeast also could incur high concentrations and an increase in the area of high ozone by a factor of three.

- Increases in ambient ozone levels resulting from climate change could increase the number of nonattainment areas and make attainment more expensive in many regions. Preliminary estimates suggest that an expenditure of several million dollars per year may be necessary for volatile organic compound (VOC) controls above those needed to meet standards without climate change. The total costs for additional air pollution controls that may be needed because of global warming cannot be estimated at this time.

- Because of the close relationship between air pollution policies and global climate change, it is appropriate for EPA to review the impact of global climate change on air policies and the impact of air pollution regulations on global climate change.

RELATIONSHIP BETWEEN CLIMATE AND AIR QUALITY

The summer of 1988 provided direct evidence of the importance of weather to pollution episodes in the United States. Despite significant progress in reducing emissions of many pollutants over the last decade, the extended stagnation periods and high temperatures caused ozone levels in 76 cities across the country to exceed the national standard by at least 25%. Whether this recent summer is an appropriate analog for the future cannot be determined with certainty, but scientists have recognized for some time that air pollution does vary with seasons and is directly affected by ventilation, circulation, and precipitation, all of which could be affected by future global climate changes.

Ventilation

Two major factors, referred to as "ventilation" when considered together, control the dilution of pollutants by the atmosphere: windspeed and the depth of the atmospheric mixing layer (frequently called the mixing depth). If windspeed is high, more air is available to dilute pollutants, thus lowering pollutant concentrations. The mixing layer (the distance between the ground and the first upper-layer inversion) tends to trap pollutants because the inversion above it acts as a barrier to vertical pollutant movement. Thus, pollutant concentrations decrease as mixing depth increases, providing greater dilution.

The ventilation characteristics of an area change, depending on whether a high- or low-pressure system is present. Low-pressure systems usually produce good ventilation because they normally have greater mixing depths and windspeeds, and precipitation is often associated with them. High-pressure systems, on the other hand, generally produce poor ventilation conditions because they frequently have smaller mixing depths on their western sides and lower windspeeds. They also tend to move more slowly than lows, so more emissions can enter their circulation patterns. In addition, they are frequently free of clouds, resulting in maximum sunlight and therefore more photochemical ozone production during the day. Also, during the evenings, the clear skies allow surface-based (see below) inversion layers to form, concentrating pollutants in a small volume of air and often creating very high air pollution levels.

Climatologically, certain places in the country, such as the Great Plains and the Northeast (Figure 11-1A), are frequently windy, and others, such as the Southwest (Figure 11-1B), frequently have large mixing depths. These areas will have cleaner-than-average air if they do not contain too many pollutant sources. Areas, such as California, that are frequently affected by high-pressure systems -causing lower windspeeds and smaller mixing depths -- will have more major air pollution episodes.

Circulation

Two semipermanent high-pressure systems are important to the global circulation pattern and greatly influence U.S. air pollution climatology. the large Pacific high, which is often situated between the Hawaiian Islands and the west coast of North America, and the Bermuda high, located over the western Atlantic Ocean.

The Pacific high often results in extended periods of air stagnation over the western United States from Oregon and California to over the Rockies, and is responsible for many severe ozone episodes in southern California. Air stagnation associated with the westward extension of the Bermuda high occurs most often during the summer months and affects the eastern United States from southern Appalachia northward to New England. Within the Bermuda high, pollutants are slowly transported from the industrial areas of the Ohio River Valley into the populated areas of the Northeast. The Bermuda high is also responsible for the general southwest-to-northeast airflow in the summer, carrying pollutants along the metropolitan corridor from Richmond to Boston and exacerbating the ozone problem in the Northeast.

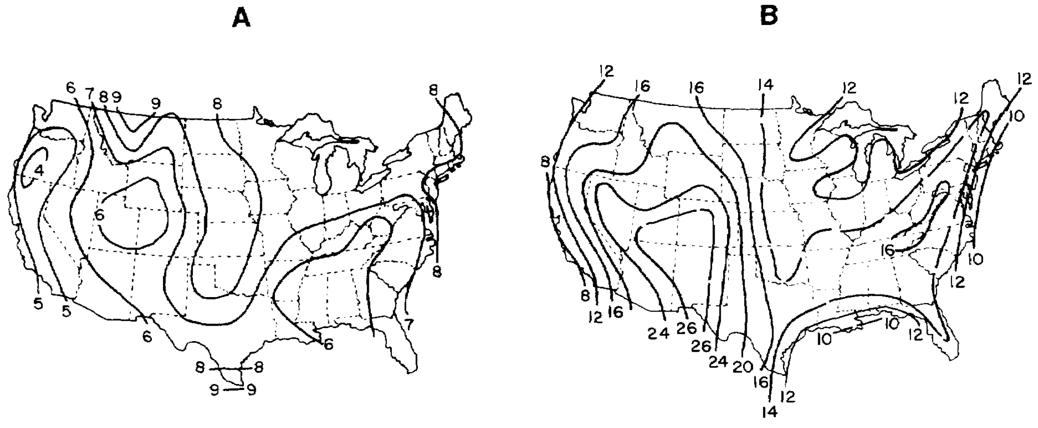

Figure 11-1. (A) Mean annual windspeed averaged through the afternoon mixing layer (speeds are in meters per second); (B) mean annual afternoon mixing height, in hundreds of meters (adapted from Holzworth, 1972).

Precipitation

Atmospheric pollutants in both particulate and gaseous forms are incorporated into clouds and precipitation. These pollutants can then be transported to the ground through rainfall (wet deposition). Cloud-formation processes and the consequent type of precipitation, together with the intensity and duration of precipitation, are important in determining wet deposition of pollutants.

PATTERNS AND TRENDS IN AIR QUALITY

To protect the public health and welfare, the U.S. EPA has promulgated National Ambient Air Quality Standards (NAAQS). In 1986, more people lived in counties with measured air quality levels that violated the primary NAAQS for ozone (O_3) than for other pollutants (Figure 11-2).

Although millions of people continue to breathe air that is in violation of the primary NAAQS, considerable progress is being made in reducing air pollution levels. Nationally, long-term 10-year (1977-86) improvements have been seen for a number of pollutants, including total suspended particulates (TSP), O_3, carbon monoxide (CO), nitrogen dioxide (NO_2) lead, and sulfur dioxide (SO_2). This section does not attempt to predict future trends in emission levels.

Total Suspended Particulates

Annual average TSP levels decreased by 23% between 1977 and 1986, and particulate emissions decreased by 25% for the same period. The more recent TSP data (1982-86) show that concentrations are leveling off, with a 3% decrease in ambient TSP levels and a 4% decrease in estimated emissions during that time.

In the future, air quality may decrease as the benefits of current pollution control measures are affected by increases in population and economic growth.

Sulfur Dioxide

Annual average SO_2 levels decreased 37% from 1977 to 1986. Aneven greater improvement was observed in the estimated number of violations of the 24-hour standard for SO_2 concentration, which decreased by 98%. These decreases correspond to a 21% drop in sulfur dioxide emissions during this 10-year period. However, most of the violations and the improvements occurred at source-oriented sites, particularly a few smelter sites. Additional reductions may be more difficult to obtain. The higher concentrations were found in the heavily populated Midwest and Northeast.

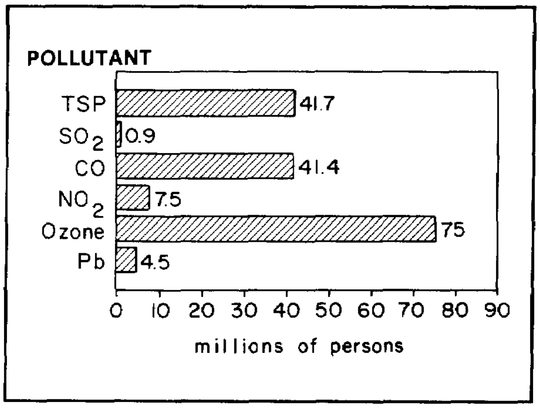

Figure 11-2. Number of persons living in counties with air quality levels above the primary National Ambient Air Quality Standards in 1986 (based on 1980 population data) (U.S. EPA, 1988).

Ozone

A national standard for ambient levels of ozone was established with the original Clean Air Act in 1972, along with standards for five other pollutants. While headway has been made in meeting all these national air quality standards, progress in meeting the ozone standard has been particularly slow and frustrating for concerned lawmakers and environmental officials at all levels of government. At the end of 1987, the date anticipated in the act for final attainment of the ozone standard, more than 60 areas had not met the standard. In recent years, the number of nonattainment areas has fluctuated with meteorology, often overwhelming the progress being made through reduced emissions. Thus "bad" weather (summertime conditions favorable to ozone formation) in 1983 led to an increased number of nonattainment areas, and "good" conditions in 1986 led to a decreased number of areas.

Nationally, between 1979 and 1986, O_3 levels decreased by 13%. Emissions of volatile organic compounds (VOCs), which are ozone precursors, decreased by 20% from 1979 to 1986. The estimated number of violations of the ozone standard decreased by 38% between 1979 and 1986. The highest concentrations were in southern California, but high levels also persisted in the Texas gulf coast, the northeast corridor, and other heavily populated regions.

Acid Deposition

Widespread concern exists concerning the effects of acid deposition on the environment. With the present monitoring network density in eastern North America, it is now possible to quantify regional patterns of concentration and deposition of sulfate, nitrate, and hydrogen ions, primary constituents of acid deposition. In Figures 11-3 through 11-5, isopleth maps show the geographic pattern of acid deposition, as reflected by the concentration and deposition of these three species (Seilkop and Finkelstein, 1987).

For the relatively short period from 1980 and 1984, evidence indicates the total deposition and average concentration of sulfate, nitrate, and hydrogen ions in precipitation falling over eastern North America decreased by 15 to 20%. The observed decreases correspond with reported reductions in the U.S. emissions of sulfur oxides (SO_X) and nitrogen oxides (NO_x), and sulfate and nitrate precursors. However, the emission figures are subject to estimation error and should be used cautiously (Seilkop and Finkelstein, 1987).

STUDIES OF CLIMATE CHANGE AND AIR QUALITY

Some of the climate factors that could affect air quality are listed in Table 11-1. To explain these relationships, two projects were undertaken for this report to identify the potential impacts of climate change on air quality:

- Climate Change and Its Interactions with Air Chemistry Perspectives and Research Needs - Penner, Connell, Wuebbles, and Covey - Lawrence Livermore National Laboratory (Volume F)

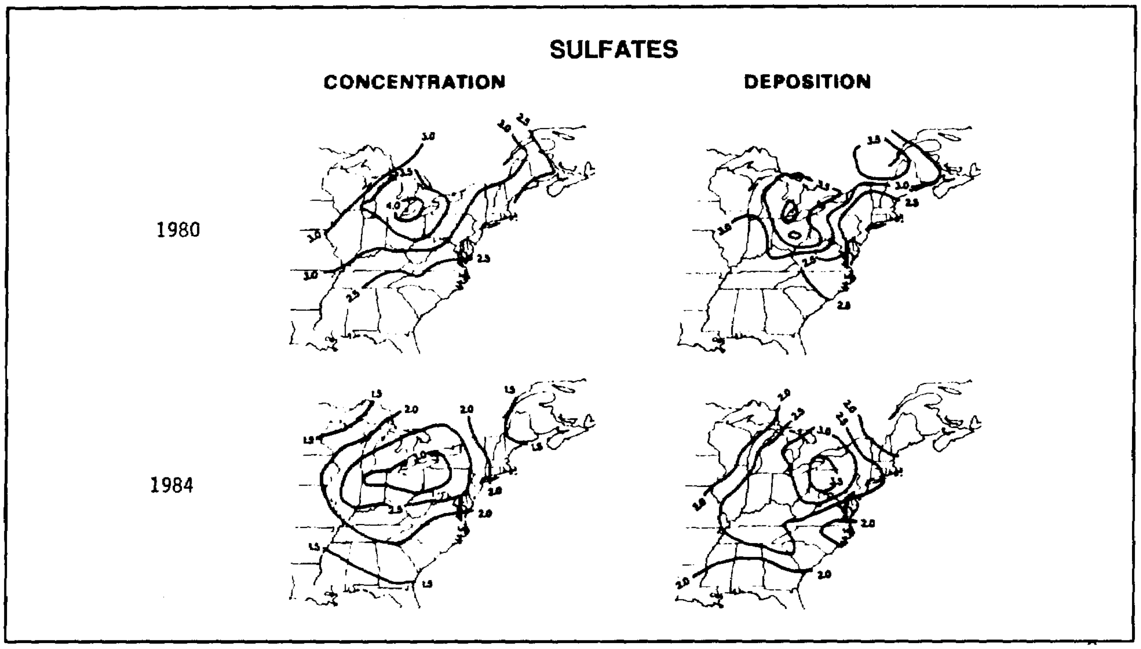

Figure 11-3. Isopleth maps of average annual concentrations (mg/liter) and total annual deposition (g/m) of sulfates in 1980-84 (Seilkop and Finkelstein, 1987).

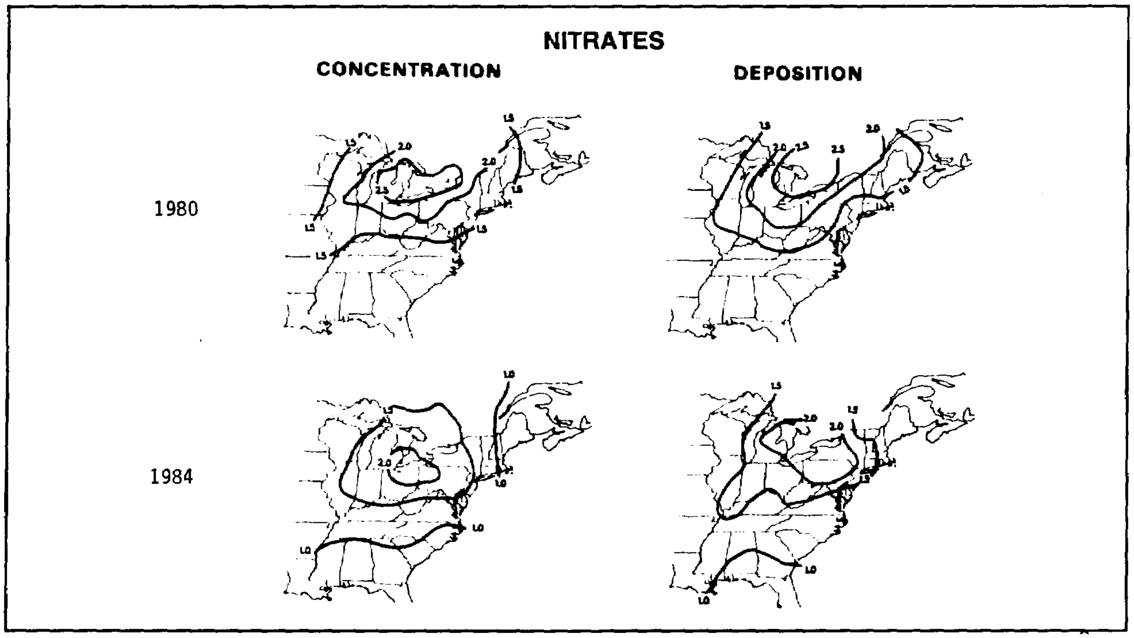

Figure 11-4. Isopleth maps of average annual concentration (mg/liter) and total annual deposition (g/m1) of nitrates in 1980-84 (Seilkop and Finkelstein, 1987).

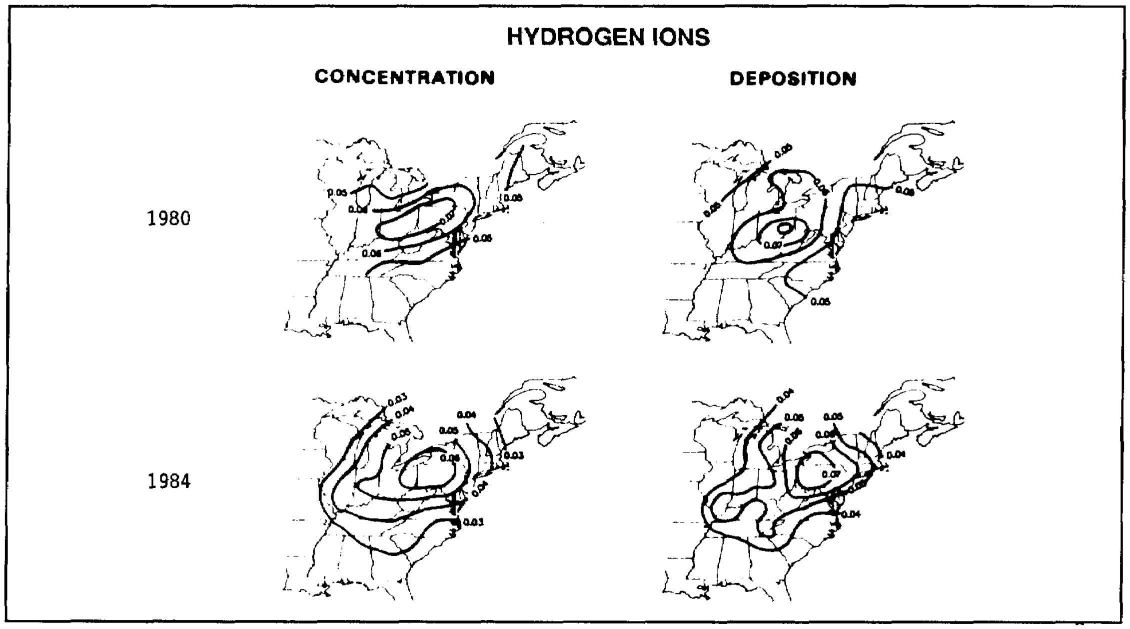

Figure 11-5. Isopleth maps of average annual concentration (mg/liter) and total annual deposition (g/m) of hydrogen ions in 1980-84 (Seilkop and Finkelstein, 1987).

Table 11-1. Climate Change Factors Important for Regional Air Quality

Changes in the following affect air quality:

1. the average maximum or minimum temperature and/or changes in their spatial distribution leading to a change in reaction rates and the solubility in gases in cloud water;
2. stratospheric O_3 leading to a change in reaction rates;
3. the frequency and pattern of cloud cover leading to a change in reaction rates and rates of conversion of SO_2 to acid deposition;
4. the frequency and intensity of stagnation episodes or a change in the mixing layer leading to a more or less mixing of polluted air with background air;
5. background boundary layer concentrations of water vapor hydrocarbons, NO_x, and O_3, leading to more or less dilution of polluted air in the boundary layer and altering the chemical transformation rates;
6. the vegetative and soil emissions of hydrocarbons and NO_x that are sensitive to temperature and light levels, leading to changes in their concentrations;
7. deposition rates of vegetative surfaces whose absorption of pollutants is a function of moisture, temperature, light intensity, and other factors, leading to changes in concentrations;
8. energy usage, leading to a change in energy-related emissions;
9. aerosol formation, leading to changes in reaction rates and the planetary albedo (reflectivity); and
10. circulation and precipitation patterns leading to a change in the abundance of pollutants deposited locally versus those exported off continent.

Source: Adapted from Penner et al. (Volume F).

- Examination of the Sensitivity of a Recional Oxidant Model to Climate Variations -Morris, Gery, Liu, Moore, Daly, and Greenfield - Systems Applications, Inc. (Volume F)

The literature does not contain studies on the effects of climate change on air quality. Thus, these studies should be considered as preliminary analyses of the sensitivity of air quality to climate change.

Climate Change and Its Interactions with Air Chemistry

Penner et al. conducted a literature review of studies on the relationship of climate and air quality. They also organized a workshop on the issue.

Effect of Climate Chance on Ozone Formation

Changes in ventilation, circulation, precipitation, and other aspects of climate affect the concentrations of the ozone precursors (VOCs and NO_x). Climate changes can also increase or decrease the rates at which these precursors react to form ozone. The effects of change in global temperature and in stratospheric ozone concentration on tropospheric ozone precursor concentrations, reaction rates, and tropospheric ozone concentrations are discussed below.

Temperature Change

Studies of the Effects of Temperature on Ozone. Smog chamber and modeling studies have shown that ozone levels increase as temperature increases. Kamens et al. (1982) have shown in an outdoor smog chamber study that the maximum ozone concentration increases as the daily maximum temperature increases (holding light intensity constant). Their data show that there is no critical "cut-off' temperature that eliminates photochemical ozone production. Instead, a general gradient is observed as a function of temperature.

Samson (1988) has recently studied ambient data for Muskegon, Michigan, and found that the number of ozone excursions above the standard (0.12 ppm) is almost linearly related to mean maximum temperature. In 1988, the mean maximum temperature was 77 F and there were 12 ozone excursions. In 1984, with a mean temperature of 73.50 F, there was only one excursion.

Temperature-dependent modeling studies were conducted by Gery et al. (1987). For this modeling effort, Gery et al. used the OZIPM-3 trajectory model, which is city specific. The scenarios for the different cities used actual observed mixing heights, solar radiation and zenith angle, and pollutant concentrations characteristic for the particular city considered for June 24, 1980. This base case was chosen because it was a high-pollution day, and ambient data were available. The increased temperature scenarios applied the increase throughout the day and were added to the base case scenario. The light intensity increase was achieved by increasing the photolyses rates for nitrogen dioxide, formaldehyde, acetaldehyde, hydrogen peroxide, and ozone. Results for New York in June 1980 are shown in Table 11-2. In general, ozone concentration increased with increasing temperature. The concentration of hydrogen peroxide (H_2O_2), a strong oxidant that converts SO_2 to sulfuric acid, was also observed to increase with higher temperatures. This is compatible with the increase in ozone because the entire photochemical reaction process is accelerated when temperature rises. As a result, cities currently violating the ozone NAAQS will be in violation to a greater degree in the future, and cities that are complying with the NAAQS now could be forced out of compliance just by a temperature increase. Figure 11-6 shows the predicted increase in low-level ozone for two temperature increases in Los Angeles, New York, Philadelphia, and Washington.

Modeling studies by Penner et al. have shown that the effect temperature has on ozone formation also depends on the ratio of volatile organic compounds to nitrogen oxides, both of which are ozone precursors. Figure 11-7 shows that ozone levels will generally go up, except in areas where the ratio of VOCs to NO_x is low.

Temperature change has a direct effect on ozone concentrations because it increases the rates of ozone-forming reactions. However, a temperature rise can also affect ozone formation by altering four other aspects of climate or the atmosphere: cloud cover, frequency and intensity of stagnation periods, mixing layer thickness, and reactant concentrations.

Table 11-2. Maximum Hourly Concentrations and Percentage Changes for Ozone, H202, and PAN for the Future Sensitivity Tests Using an EKMA Model for the Simulation of June 24, 1980, New York

Ozone	Concentration (ppm)			Percent change (from base)		
Change in Temp (°C)	0	+2	+5	0	+2	+5
Stratospheric Ozone[a]						
Base	0.125	0.130	0.138	--	4	10
-16.6%	0.150	0.157	0.167	20	26	34
-33.3%	0.165	0.170	0.178	32	36	42

Hydrogen Peroxide (H2O2)						
Change in Temp (°C)	Concentration (ppb)			Percent change (from base)		
Stratospheric Ozone[a]						
Base	0.05	0.06	0.08	--	20	60
-16.6%	0.43	0.58	0.84	760.0	1060	1580
-33.3%	3.08	3.31	3.60	6060.0	6520	7100

Peroxyacetyl Nitrate (PAN)						
Change in Temp (°C)	Concentration (ppb)			Percent change (from base)		
Stratospheric Ozone[a]						
Base	0.05	0.06	0.08	--	20	60
-16.6%	0.43	0.58	0.84	760.0	1060	1580
-33.3%	3.08	3.31	3.60	6060.0	6520	7100

[a] Base refers to the present stratospheric ozone column. The -16.6 and -33.3% refer to a depletion of the base value. Ultraviolet light will increase with the depletion (Gery et al., 1987).

Effect of Changes in Cloud Cover. The reduction in light intensity caused by increased cloud cover can reduce ozone production. Penner et al. (Volume F) calculate that a reduction in light intensity of 50% throughout the day will reduce the ozone formation. However, the magnitude of ozone reduction depends on the time of day when the cloud cover occurs. If clouds occur in the afternoon or evening, little effect is observed in the ozone production, but if clouds occur during the morning hours, photochemical reactions are slowed, and less ozone is produced. Jeffries et al. (1989) suggest that cloud cover can decrease ultraviolet radiation by 7 to 14% in their outdoor smog chamber located in North Carolina. Although a global temperature change would affect cloud cover, the type and direction of the change are unknown.

The Penner et al. study assumes that cloud cover causes an equal decrease in all wavelengths of solar radiation. However, clouds are not expected to cause an equal decrease at all wavelengths. Solar radiation is needed to form ozone. Since Penner et al.

may have underestimated the intensity of some wavelengths of light, they may have overestimated the decrease in ozone production.

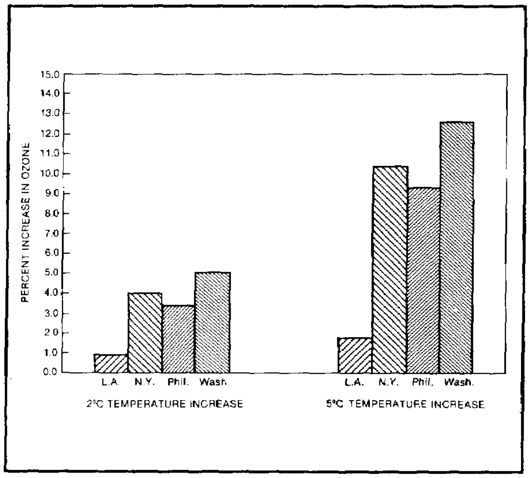

Figure 11-6. Percent increase in predicted O_3 over future base case (0.12 ppm) for two temperature increases in four cities (Gery, 1987).

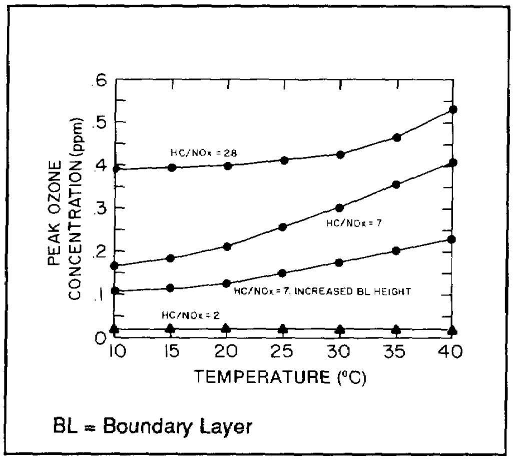

Figure 11-7. The effect of temperature on the peak O_3 concentrations predicted in a box model calculation of urban O_3 formation. Calculations are shown for three hydrocarbon to NO_x ratios. The effect of increasing the boundary layer depth for the case with a hydrocarbon to NO_x ratio of 7 is also shown (Penner et al., Volume F).

<u>Effect of Water Vapor</u>. Water vapor is involved in the formation of free radicals (reactive compounds) and hydrogen peroxide, which are necessary for the formation of ozone. Global increases in temperature are expected to raise tropospheric water vapor levels.

If sources of water vapor are not perturbed by vegetative changes, and if global circulation patterns do not significantly affect precipitation events (an unlikely assumption), then global water vapor levels are expected to increase with increasing temperature. A temperature increase of 2 C could raise the water vapor concentration by 10 to 30% (Penner et al., Volume F). This change should affect both oxidant formation and sulfur dioxide oxidation (acid deposition).

Smog chamber studies have shown that at high pollutant levels, increases in water vapor can significantly accelerate both the reaction rates of VOCs and the rate of oxidant formation (Altshuller and Bufalini, 1971). Walcek (1988) has shown with the use of a regional acid deposition model (RADM) that the ozone, hydrogen peroxide, and sulfate production rates in the boundary layer of the troposphere all increase with increasing water vapor.

<u>Effect of Changes in Frequency and Intensity of Stagnation Periods</u>. As noted previously, highpressure systems significantly enhance ozone formation potential. During a high-pressure episode, pollutants are exposed to high temperatures and prolonged irradiation (Research Triangle Institute, 1975), resulting in high levels of ozone. If the intensity and frequency of high pressure episodes increase with global warming, then ozone levels can be expected to be even higher.

<u>Effect of Changes in Mixing Layer Thickness</u>. As shown in Figure 11-7, increases in the mixing layer height decrease ozone formation, presumably because there are less ozone precursors per volume of atmosphere. An increase of global temperature would probably lead to an increase in average mixing depths as a result of greater convection, which raises the mixing depth and increases mixing.

<u>Effect of Changes in Reactant Concentrations</u>. The concentrations of ozone precursor pollutants (VOCs, NO_x) play a large part in determining the amount of ozone produced. With increasing temperature, natural hydrocarbon emissions are expected to increase. Also, unless preventive measures are taken, manmade emissions would increase (vapor pressure of VOCs increases with increasing temperature). If these ozone precursors increased in concentration, ozone production would increase.

Lamb et al. (1985) have shown that natural hydrocarbon (VOC) emissions from deciduous forests would increase by about a factor of three with a temperature change from 20° to 30°C. However, as discussed in Chapter 5: Forests, the abundance of some deciduous forests could decline because of global warming. However, grasslands or shrubs that replace forests would still emit hydrocarbons. The net effect is probably uncertain. Emissions of NO from powerplants would grow because of a greater demand for electricity during the summer months. Soil microbial activity is also expected to increase with increasing temperature. This will increase natural emissions of NO_x. Evaporative emissions of VOCs from vehicles and refueling would also be expected to rise with warmer temperatures. However, exact predictions of the effects of all these factors on ozone formation are difficult to make because the relationship between precursor emissions and ozone is extremely complex and not fully understood, and because increases in emissions are difficult to quantify.

An example of this complex relationship between ozone and its precursors is shown in Figure 11-8 (Dodge, 1977). At high VOC levels and low NO_x, adding or reducing VOCs has very little effect on ozone formation. Likewise, when NO_x concentrations are high and VOC concentrations are low, increasing NO_x reduces ozone formation while lowering NO_x increases ozone formation. Thus, VOCs and NO_x must be examined together when considering any ozone reduction strategy based on controlling ozone-forming precursors.

Stratospheric Ozone Change

Changes in stratospheric ozone concentration can also affect tropospheric ozone formation because stratospheric ozone regulates the amount of ultraviolet (UV) radiation available for producing ozone in the troposphere. Stratospheric ozone absorbs UV light from the sun and decreases the UV energy striking the Earth's surface. When stratospheric ozone is depleted by the chlorofluorocarbons (CFCs) generated by human activity, more UV radiation reaches the Earth's surface, which increases the photolysis rates[1] of compounds that absorb solar radiation (NO_2, formaldehyde, acetaldehyde, O_3, and H_2O_2)Faster photolysis produces more free radicals (high-energy species) that increase the amount of smog. Thus, less stratospheric ozone will lead to enhanced ozone formation in the troposphere.

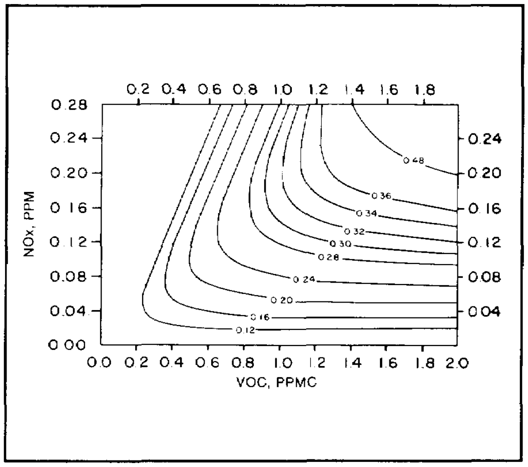

Figure 11-8. Ozone isopleths as a function of NO_x and volatile organic compounds (VOCs) (Dodge, 1977).

Modeling results for New York from Gery et al. (1987) show that tropospheric ozone increased when stratospheric ozone decreased (see Table 11-2). They also show that H_2O_2 and peroxyacetyl nitrate (PAN) yields increase. H_2O_2 is a strong oxidant that converts SO_2 to sulfuric acid, and PAN is an air pollutant that damages plants and irritates eyes. The 16.6 and 33.3% decreases (Table 11-2) in stratospheric ozone far exceed the expected decrease resulting from the buildup of CFC concentrations. This is especially true since the Montreal Protocol agreement will limit CFC production. These high values of stratospheric ozone depletion are used only for illustrative purposes.

Changes in Tropospheric Hydroxyl Radicals

Hydroxyl radicals (reactive compounds) are the most important free radicals found in the atmosphere. These reactive compounds are responsible for removing many atmospheric pollutants (such as CH_4, VOCs, methyl chloroform, CO) from the atmosphere (Penner et al., Volume F). Without these free radicals, pollutants would not be removed from the atmosphere and would build up to higher levels (global heating would be greater). Hydroxyl radicals in the free troposphere are produced primarily by the decomposition of ozone by

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[1] Photolysis is the breakdown of chemicals as a result of the absorption of solar radiation.

sunlight and the subsequent reaction of high-energy oxygen with water. In the urban atmosphere, hydroxyl radicals are produced through a complex series of reactions involving VOCs, nitrogen oxides, and sunlight. The solar photolysis of hydrogen peroxide also gives rise to hydroxyl radicals. This occurs in both urban and rural areas.

The effect of global climate changes on hydroxyl radical abundance is unclear. In urban areas with increases in VOCs and NO_x, a temperature increase will increase hydroxyl radical concentration. Also, if natural hydrocarbons and NO_x increase in rural areas, hydroxyl radicals are expected to increase. However, if methane, CO, and natural hydrocarbons increase without an additional increase in NO_x, then hydroxyl radicals will be depleted. A definitive prediction on the effect of increasing temperature on global concentrations of hydroxyl radicals cannot be made at this time.

Effect of Climate Change on Acid Deposition

Rainwater and surface waters are more acidic than natural background levels because of industrial and mobile emissions of SO_2 and NO_x , which form sulfuric and nitric acids in the atmosphere. In the air, sulfuric acid (H_2SO_4) is produced primarily by the reaction of SO_2 with hydroxyl radicals (high energy species); in clouds, the oxidation of SO_2 to H_2SO_4 is more complex, involving reactions with hydrogen peroxide and other dissolved oxidants. Nitric acid (HNO_3) is produced in air by the reaction of hydroxyl radicals with NO_x.

Organic acids, such as formic and acetic acids, are also formed in the atmosphere. However, their relative importance to the acid deposition ,.problem is unknown at present. Because they are weak acids (compared to H_2SO_4 and HNO_3), their contribution to the problem is expected to be much less than that of the inorganic acids (Galloway et al., 1982; Keene et al., 1983, 1984; Norton, 1985).

The acids produced in the atmosphere can be "dry deposited" to the Earth's surface as gases or aerosols, or they can be "wet deposited" as acid rain. Changes in total acid levels depend on changes both in atmospheric chemistry and changes in precipitation. Wet deposition is affected most by the amount, duration, and location of precipitation. Since the direction of regional precipitation changes is unknown, it is not known whether acid rain will increase or decrease in the future. However, many of the same factors that affect ozone formation will also affect the total deposition of acids.

Temperature Change

Higher temperatures accelerate the oxidation rates of SO_2 and NO_x to sulfuric and nitric acids. Gery et al. 1987) have shown that a temperature rise would also speed the formation of H_2O_2, increasing the conversion of SO_2 to sulfuric acid (see Table 11-2). Hales (1988) studied the sensitivity to a 10°C temperature rise using the storm-cloud model PLUVIUS-2. Considering only the chemistry occurring with a 10°C temperature rise, sulfate production increased 2.5 times. No modeling was performed at more modest temperature increases (e.g., ~4°C); however, it is likely that oxidation would also increase with a smaller increase in temperature. The limiting factor in the oxidation of SO_2 appears to be the availability of H_2O_2. The model also suggested that a temperature increase would cause more sulfuric acid to form near the sources where SO_2 is emitted.

<u>Effect of Global Circulation Pattern Changes</u>. Potential changes in global circulation patterns would greatly affect local acid deposition, because they would alter ventilation and precipitation patterns. Galloway et al. (1984) have calculated that over 30% of the sulfur emissions from the eastern United States are transported to the north and farther east. Changes in circulation patterns would affect this transport, although the direction or magnitude of the effect is unknown.

<u>Effects of Changes in Emissions</u>. If electricity demand rises with rising temperatures (see Chapter 10: Electricity Demand), if more fossil fuels are burned, and if technology is not improved, SO_2 and NO_x emissions will increase. An approximate 10% growth in use of electricity in the summer could increase SO_2 emissions during the summer by approximately 30% if present-day technology is used in the future. This, in turn, would increase acid deposition.

<u>Effects of Reduced Stratospheric Ozone</u>. A decrease in stratospheric ozone due to CFCs may increase acid deposition because more UV radiation would be available to drive the chemical reactions. As discussed above, a modeling study by Gery et al. (1987) showed an increase in the yield of H_2O_2 when

stratospheric ozone was reduced by 16 and 33%. Because H20z is a strong oxidant, SO_2 would probably also be oxidized more quickly into sulfate aerosols and acid rain, but this depends on the availability of water vapor (e.g., clouds, rain). Implementation of the Montreal Protocol should help reduce CFC emissions.

Reduced Visibility. The growth in natural organic emissions and increases in sulfates resulting from warmer temperatures should reduce visibility, assuming that the frequency of rain events, wind velocity, and dry deposition rates remain the same. If rain events increase, washout/rainout should increase and visibility would be better than predicted (see Chapter 3: Climate Variability).

MODELING STUDY OF CLIMATE AND AIR QUALITY

Study Design

Morris et al. (Volume F) applied a regional transport model RTM-111 to an area covering central California and a region covering the midwestern and the southeastern United States. The model was run for the present-day conditions and for a future climate. For California, Morris et al. used input data from August 5-10, 1981; for the Midwest and the Southeast, they used input data from July 14-21, 1981. These were periods with high ozone levels and may be most sensitive to changes in climate. The scenario assumed that temperatures would be 4°C warmer than in the base case, but all other climate variables were held constant (relative humidity was held constant). The scenario assumed no change in emission levels, no change in boundary layer, and no change in wind velocity.

The RTM-111 is a three-dimensional model that represents point sources embedded in a grid framework. The model has three prognostic vertical layers and a diagnostic surface layer. This means that the surface layer is represented by actual observations. The other three layers are predicted by using the surface layer data. The photochemical reactions are based on the latest parameterized chemical mechanism.

Limitations

Perhaps the most important limitation is that emission levels were held constant. It is likely that future emission levels will be different, although this study did not estimate how. The results of this study are useful for indicating the sensitivity of ozone formation to temperature, but should not be considered as a prediction of future ozone levels. The model ignored future increases in emissions that would occur with increased temperatures. The estimates for ozone are only coarse approximations. Morris et al. used the National Acid Precipitation Assessment Program (NAPAP) emissions data of 1980. These data appear to underestimate actual ratios of VOCs to NO as measured in urban areas. Ching et al. (1986) state that for most cities, the NAPAP data underestimate VOC emission values by a factor of three or more. The model simplified some reactions of the hydrocarbons (VOCs) because the chemistry is not well known.

This study did not estimate climate-induced alterations in most meteorological variables, except temperature and water vapor, which is an oversimplification. For example, this study assumed that the mixing heights remain unchanged for the temperature increase scenario; in reality, mixing heights could increase with rising temperature. Holding the mixing heights constant probably overemphasized the importance of temperature in oxidant production, because an increased mixing layer depth might have had a dilution effect. Also, as stated earlier, cloud cover will affect ozone production. If cloud cover increases, then ozone is expected to decrease. Frequency and intensity of stagnation periods can also have profound effects on ozone formation. This modeling exercise did not consider these factors.

Results

Central California Study

Table 11-3 summarizes the results from the base case scenario and a climate sensitivity scenario that used a 4°C temperature increase and an attendant increase in water vapor concentration. All of the days studied show a larger area exposed to high levels of ozone. An increase in temperature may lengthen the duration of high ozone levels, although the maximum levels may be the same. Figure 11-9 illustrates the

August 6 base case and climate sensitivity case. The temperature change increased the August 6 maximum ozone concentration from 15 parts per hundred million (pphm) to 18 pphm, a 20% increase in ozone. The area in which the NAAQS was exceeded almost doubled from 3,700 to 6,600 square kilometers.

The temperature increases in the two main cities in the San Joaquin Valley (Fresno and Bakersfield) resulted in an approximate 0.5-pplun increase (approximately 8%) in maximum daily ozone concentration. In regions farther away from the emissions, such as the Sierra Nevada Mountains, little change in ozone levels was observed with the increased temperature.

Midwest and Southeast Study

The results from applying RTM-III to the midwestern and southeastern areas are shown in Table 11-4. On one particular day (July 16), raising the temperature caused maximum ozone to increase from 12.5 pphm to 13.0 pphm (Figure 11-10). Although this is only a slight increase (0.5 pphm), the predicted area of exceedance of the ozone NAAQS increased by almost a factor of three, from 9,800 to 27,000 square kilometers. The differences occurred mainly in the upper Midwest. In general, the results range from a reduction of 2.4% to an increase of 8.0% in ozone levels. Although a temperature increase will generally increase ozone formation, it is noted in Table 11-4 that on two days, July 14 and July 21, no ozone increases were observed. This occurs when there are insufficient precursors to sustain ozone formation. Under these conditions, ozone is produced more quickly with increasing temperature but the total amount produced need not be greater and could even be less in some cases.

Both modeling exercises indicate that temperature change alone could increase ozone levels over what they would be without climate change.

Table 11-3. Maximum Daily Ozone Concentrations Predicted by the RTM-111 for Each Day of the Central California Modeling Episodes for the Base Case and the Case of Climate Sensitivity to Increased Temperature of 4 C

	Maximum daily ozone concentrations (ppbm)		
Date of Episode (1981)	Base case	4°C temperature increase	Percent increase
August 5	11.8	12.1	3
August 6	15.0	18.0	20
August 7	11.7	13.1	12
August 8	13.5	13.7	2
August 9	10.5	11.2	7
August 10	9.1	9.18	8

Source: Morris et al. (1988).

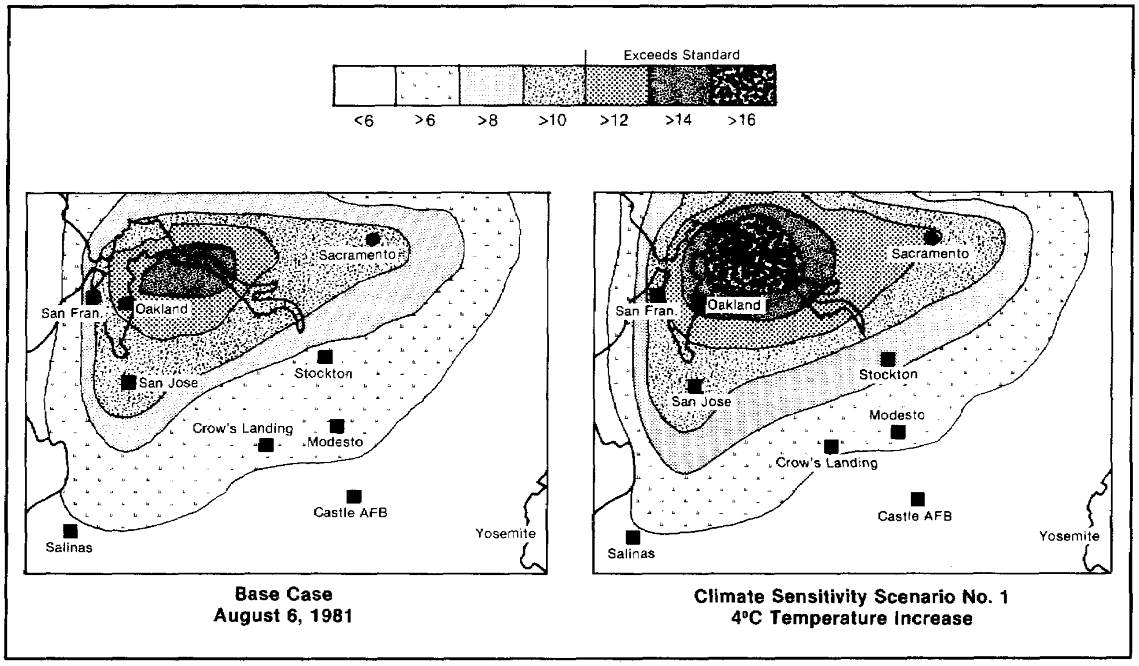

Figure 11-9. Comparison of estimated maximum daily ozone concentrations (pphm) for the base case and climate sensitivity scenario No. 1 (temperature and water increase) for August 6, 1981 (Morris et al., 1988).

Table 11-4. Maximum Daily Ozone Concentrations Predicted by the RTM-111 for Each Day of the Midwestern/Southeastern Episode for the Base Case and the Case of Increased Temperature of 4°C

	Maximum daily ozone concentrations (ppbm)		
Date of Episode (1981)	Base case	4°C temperature increase	Percent increase
July 14	11.3	11.3	0.0
July 15	11.5	11.9	3.5
July 16	12.5	13.0	4.0
July 17	11.7	12.0	2.6
July 18	11.2	12.1	8.0
July 19	13.8	14.8	7.2
July 20	11.1	11.2	0.9
July 21	12.6	12.3	-2.4

Source: Morris et al. (1988).

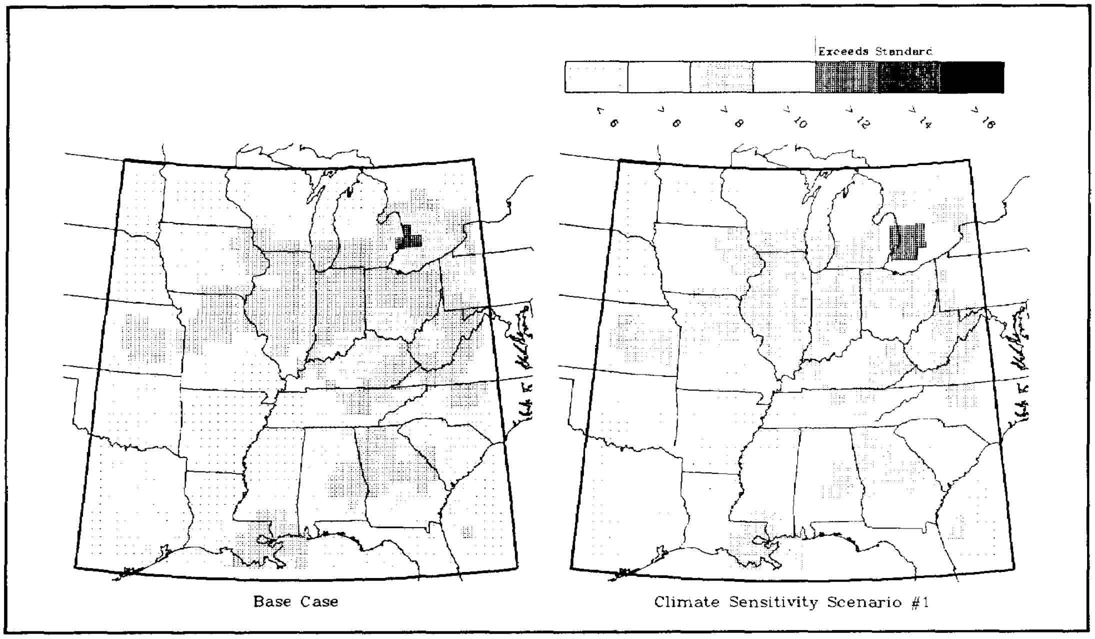

Figure 11-10. Comparison of predicted estimated maximum daily ozone concentrations (pplun) for the base case and climate sensitivity scenario No. 1 (temperature and water increase) for July 16, 1980 (Morris et al., 1988).

Population Exposure

As discussed above, both the California and Midwest/Southeast studies show a significant increase in the area that is potentially exposed to higher levels of ozone when the temperature is increased as compared with base case conditions. Data taken from the 1980 census from central California and the midwestern and southeastern areas were used to determine the number of people exposed to ozone for the base case and a 4°C temperature rise scenario. Table 11-5 presents the number of people-hours of exposure to ozone concentrations exceeding 8, 12, and 16 pphm. These estimates of human exposure were generated by multiplying the number of people in the grid cells by the total number of hours that the estimated hourly ozone concentration in those grid cells exceeded the 8-, 12-, or 16-pphm levels. Actual exposure levels may be less because indoor levels are generally lower than ambient air levels.

ECONOMIC, ECOLOGICAL, AND ENVIRONMENTAL IMPLICATIONS

Ozone

An increase in ozone levels due to climate change is important for several reasons:

- Ozone itself is a radiatively important gas and contributes to climate change. Ozone absorbs infrared energy much like carbon dioxide. It has been calculated that a 15% increase in tropospheric ozone could lead to a 0.1 C rise in global temperature (Ramanathan et al., 1987).
- Ozone levels in many areas are just below the current standard. If emissions are not reduced, any increase in ozone formation may push levels above the standard.

Table 11-5. Number of People-Hours of Exposure to Ozone Concentrations in Excess of 8, 12, and 16 pphm for the Base Case and the Case of Climate Sensitivity to Increased Temperature

Scenario	Exposure to $O_3 \geq$ 8 pphm	Exposure to $O_3 \geq$ 12 pphm	Exposure to $O_3 \geq$ 16 pphm
		Central California Modeling Episode	
Base case	70,509,216	660,876	0
Increased temperature	102,012,064	2,052,143	92,220
		Midwestern/Southeastern Modeling Episode	
Base case	1,722,590,208	29,805,348	0
Increased temperature	1,956,205,568	47,528,944	0

Source: Morris et al. (1988).

- Many inexpensive controls for ozone are already in place in nonattainment areas. Increases in ozone levels would require relatively expensive measures to sufficiently reduce ozone precursors to attain the standard.
- The standard itself is defined in terms of the highest levels of ozone experienced in an area, not average levels. (As a yearly average, no area of the country would exceed the standard of 0.12 ppm.) Thus, a factor such as temperature that may have a modest effect on average levels of ozone formation may have a much more significant effect on peak levels.

A rough estimate of each of these factors can illustrate the potential policy problems created by a rising temperature scenario. The data in Figure 11-9 suggest that 4 C degree rise in temperature may lead to an increase in peak ozone concentrations of around 10%. A 10% increase in peak ozone levels could affect a number of potential ozone violations. In the 1983-85 period for example, 68 areas showed measured exceedances of the ozone air quality standards (for technical and legal reasons, not all these areas were officially designated nonattainment areas). A 10% increase in ozone levels in that period doubled the number of nonattainment areas to 136. This would include 41 new metropolitan statistical areas (MSAs) added to the list and 27 non-MSAs. These new nonattainment areas would add most midsize and some small cities in the Midwest, South, and East to the list of nonattainment areas.

The policy implications of this should be put into context because the full effect of climate change may not be felt until well into the next century. Over the next several decades, various national measures to reduce ozone precursors, such as a reduction in the volatility of gasoline, may go into effect. These would provide a cushion to marginal areas and could offset a temperature effect. However, other factors suggest that rising temperatures could be a problem.

Ozone levels and ozone precursors are closely related to economic expansion and population growth. Consumer solvents (e.g., paints, sprays, and even deodorants) area major source of ozone precursors. These are very difficult to control and are likely to increase in the future in areas currently attaining the standards. Growth in other sources of ozone precursors would bring many areas relatively close to the limits of the ozone standard. Gradual increases in temperature would make remaining in compliance with the standard more difficult. Although any sudden change in the number of nonattainment areas as a result of a secular trend toward increased temperature is unlikely, a number of small to midsize cities eventually may be forced to develop new control programs.

The implications of warmer temperatures for existing nonattainment areas can also be estimated. In these areas, existing and planned control measures may not be adequate to reach the standard, if additional ozone forms. In the past, EPA has attempted to project the emission reductions and costs associated with the attempts of existing nonattainment areas to reach the ozone standard. Using the same modeling approach, the effects of a temperature increase were analyzed to estimate the additional tons and costs associated with a projected temperature rise. Extrapolations of existing inventories to the year 2000 suggest that higher temperatures could require an additional reduction of 700,000 tons of VOC from an inventory of about 6 million tons. Given that most current nonattainment areas already will have implemented the most inexpensive measures, these additional reductions may cost as much as $5,000 per ton per year. Their aggregate cost could be as much as $3.5 billion each year.

These conclusions should be viewed as preliminary. Nonetheless, they demonstrate that the potential economic consequences could be significant for an already expensive program to combat ozone.

Acid Rain

The global climate change is likely to affect acidic deposition in the near future for several reasons.

First, emissions from fossil fuel powerplants both influence acid rain and contribute to global warming. In the future, global warming may increase energy demand and associated emissions. Because the growth in demand for electricity in northern states (see Chapter 10: Electricity Demand) may be lower than in southern states, regional shifts in emissions may occur in the future.

Second, global climate change would influence atmospheric reaction rates and the deposition and form of acidic material. It is conceivable that regions of high deposition may shift or that more acid rain may be transported off the North American continent. Strategies that seek to control powerplants in regions near sensitive areas may or may not be as effective, as global climate change occurs.

Third, global climate change may alter the impacts of acid rain on ecological and other systems in as yet unpredictable ways. For example:

- Changes in the amount of rainfall may dilute the effect of acid rain on many sensitive lakes.
- Changes in clouds may alter the fertilization of high-elevation forests.
- Changes in humidity and frequency of rain may alter degradation rates for materials.
- Increased midcontinental dryness would alter the amount of calcium and magnesium in dust, neutralizing impacts on soils.
- Increased numbers of days without frost would decrease forest damage associated with frost and overfertilization by atmospheric nitrogen.
- Changes in snowpack and the seasonality of rainfall would change acid levels in streams and alter the timing and magnitude of spring shocks on aquatic species.

Finally, solutions to both problems are inextricably linked. Some solutions, such as SO_2 scrubbers and clean coal technologies, may abate acid rain levels, but they may do little to improve air quality or may increase global warming. Other solutions, including increased energy efficiency and switching fuels to natural gas or to renewable energy sources, may provide positive solutions to both problems.

In summary, an examination of the time horizons of importance to both acid rain and global climate change problems suggests that these two issues should not be viewed in isolation. Emissions, atmospheric reaction rates, pollutant transport, and environmental impacts will likely be altered by climate change. This suggests that a more holistic approach must be taken to air pollution problems and that proposed solutions should be evaluated on the basis of their contributions to solving both problems.

POLICY IMPLICATIONS

The Environmental Protection Agency issues air pollution regulations to improve air quality and to protect public health and welfare. In general, current regulations to reduce oxidant levels will also provide positive benefits toward a goal of limiting the rate of growth in global warming. Other programs aimed at reducing carbon monoxide levels, particularly from mobile sources, or CFCs to protect the stratospheric ozone layer, also positively affect greenhouse gases and the rate of global warming. However, the regulatory activities of the Agency have not been retrospectively reviewed to determine their impacts on global warming. In some cases, there may be important benefits; for example, current emission standards for automobiles do not encourage more efficient use of gasoline. A different form of standard, while potentially disruptive to air pollution efforts, might produce positive greenhouse gas benefits via reduced energy consumption. These issues will have to be analyzed in the future.

Because of the climate change issue, the following are some of the more important policy issues:

- Air pollution control agencies should as EPA should undertake a broad review to determine the impact of global climate change on air pollution policies. In particular, the cost of added controls resulting from climate change should be determined, perhaps as each significant regulation is proposed or reevaluated.
- The impact of EPA regulations, particularly the impact on energy use and greenhouse gases, should be a more important weight in future regulatory decisions. Since EPA regulations often serve as models for other countries, the cost penalty for better energy usage, while sometimes small in the United States, may be important on a global basis.
- Future reports to Congress and major assessments of ecological effects, e.g., the 1990 Acid Deposition Assessment document, should include sensitivity analyses of alternative climates. Risk management decisions of the Agency could then be made with improved knowledge of climate impacts.

RESEARCH NEEDS

Some of the key questions that need to be resolved regarding climate change and air quality include the following: How important will climate change be relative to other factors such as population growth to future air pollution problems? Is the impact of climate change likely to be significant enough to require totally different air pollution strategies? What mix of control strategies could be most cost effective in reducing acid rain, global warming, tropospheric ozone, and other pollution problems? The research elements needed to address these issues include basic research, sensitivity analyses, full-scale atmospheric modeling, and cost-effectiveness studies. Examples are presented below:

Basic Research - There is an important need to understand how manmade and natural emissions of hydrocarbons and other pollutants might change in the future when temperature, CO_2, and UV-B radiation increase and other climate parameters vary.

Sensitivity Analyses - Analyses of ozone concentrations are dependent on boundary layer height, clouds, water vapor, windspeed, UV-B radiation, and other parameters. Sensitivity tests using single models could improve our understanding of the relative importance of these variables and could provide important information for general circulation modelers.

Full-Scale Modeling - Complete understanding of the interactions of climate change and air quality will ultimately require that general circulation models and mesoscale chemistry models be linked in some direct or indirect manner. This will require the development of innovative approaches between the general circulation and air pollution modeling communities.

Cost-Effectiveness Studies - There are currently a number of congressional proposals to improve the Clean Air Act and to reduce global climate change. To assume that both air quality and global climate change goals are achieved, analyses of the cost-effectiveness of alternating strategies will be necessary.

REFERENCES

Altshuller, A.P., and J.J. Bufalini. 1971. Photochemical aspects of air pollution. Environmental Science and Technology 5:39-64.

Ching, J.K.S., J.H. Novak, K.L. Schere, and F.A. Schiermeier. 1986. Reconciliation of Urban Emissions and Corresponding Ambient Air Concentrations Using Mass Flow Rate Technique. Draft report prepared for EPA/ORD; April.

Dodge, M.C. 1977. Effect of Selected Parameters on Predictions of a Photo-Chemical Model. EPA

600/3-77/048. Research Triangle Park, NC: U.S. Environmental Protection Agency. June.

Galloway, J.N., G.E. Likens, W.C. Keene, and M.M. Miller. 1982. The composition of precipitation in remote areas of the world. Journal of Geophysical Research 87:8771-8788.

Galloway, J.N., D.M. Whelpdale, and G.T. Wolff. 1984. The flux of sulfur and nitrogen eastward from North America. Atmospheric Environment 18:2595-2607.

Gery, M.W., R.D. Edmond, and G.Z. Whitten. 1987. Tropospheric Ultraviolet Radiation: Assessment of Existing Data and Effect on Ozone Formation. EPA Report 600/3-87/047. Research Triangle Park, NC: U.S. Environmental Protection Agency. October.

Hales, J. 1988. In: Sensitivity of Urban/Regional Chemistry to Climate Change: Report of the Workshop, Chapel Hill, NC. Wuebbles, D.J., and J.E. Penner, eds. Livermore, CA: Lawrence Livermore National Laboratory. Feb. 17-18.

Holzworth, G.C. 1972. Mixing Heights, Windspeeds and Potential for Urban Air Pollution Throughout the Contiguous United States. Research Triangle Park, NC: U.S. Environmental Protection Agency, Office of Air Programs. Publication No. AP-101.

Jeffries, H.E., K.G. Sexton, J.R. Arnold, and T.L. Kole. 1989. Validation Testing of New Mechanisms with Outdoor Chamber Data, Volume 4: Appendixes to Photochemical Reaction Photolysis Rates in the UNC Outdoor Chamber. EPA/600/389/0l0d. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Kamens, R.M., H.E. Jeffries, K.G. Sexton, and A.A. Gerhardt. 1982. Smog Chamber Experiments to Test Oxidant-Related Control Strategy Issues. EPA 600/3-82-014. Research Triangle Park, NC: U.S. Environmental Protection Agency. August.

Keene, W.C., J.N. Galloway, and J.D. Holden Jr. 1983. Measurement of weak organic acidity in precipitation from remote areas of the world. Journal of Geophysical Research 88:5122-5130.

Keene, W.C., and J.N. Galloway. 1984. Organic acidity in precipitation of North America. Atmospheric Environment 18: 2491-2497.

Lamb B.K., H.H. Westberg, T. Quarles, and D.L. Flyckt. 1985. Natural Hydrocarbon Emission Rate Measurements From Selected Forest Sites. EPA-600/3-84-001. Research Triangle Park, NC: U.S. Environmental Protection Agency. October.

Norton, R.B. 1985. Measurements of Formate and Acetate in Precipitation at Niwot Ridge and Boulder, Colorado. Geophysical Research Letters 12:769-772.

Ramanathan, V., L. Callis, R. Cess, J. Hansen, I. Isaksen, W. Kuhn, A. Lacis, F. Luther, J. Mahlman, R. Reck, and M. Schlesinger. 1987. Climatechemical interactions and effects of changing atmospheric trace gases. Review Geophysics 25:1441-1482.

Research Triangle Institute. 1975. Investigation of Rural Oxidant Levels As Related to Urban Hydrocarbon Control Strategies. EPA-450/3-75036. Research Triangle Park, NC: U.S. Environmental Protection Agency. March.

Samson, PJ. 1988. Linkages Between Global Climate Warming and Ambient Air Quality. Paper presented at the Global Climate Linkages Conference, Washington, DC; Nov. 15-16.

Seilkop, S.K., and P.L. Finkelstein. 1987. Acid precipitation patterns and trends in eastern North America, 1980-84. Journal of Climate and Applied Meteorology 26(8):980-994.

U.S. EPA. 1988. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. National Air Quality and Emissions Trends Report, 1986. Research Triangle Park, NC: U.S. Environmental Protection Agency. EPA report No. 45014-88-001. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Walcek C. 1988. In: Sensitivity of Urban/Regional Chemistry to Climate Change: Report of Workshop, Chapel Hill, NC.

Wuebbles, DJ. and J.E. Penner, eds. Livermore, CA: Lawrence Livermore National Laboratory. Feb. 17-18.

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CHAPTER 12
HUMAN HEALTH

FINDINGS

Global warming may lead to increases in human illness (morbidity) and mortality during summer. Populations at particular risk are the elderly and very young (age 1 year and below), particularly those who are poor and/or homeless. These effects may be more pronounced in some regions than in others, with northern regions more vulnerable to the effects of higher temperature episodes than southern regions. Milder winters may offset increases in morbidity and mortality, although net mortality may increase. Mortality in southern cities currently shows a lesser effect from heat waves, presumably because populations have acclimatized. If northern populations show this same acclimatization, the impact of global warming on summer mortality rates may be substantially lower than estimated. The full scope of the impacts of climate change on human health remains uncertain and is a subject for future research.

- Although there may be an increase in weather related summer deaths due to respiratory, cardiovascular, and cerebrovascular diseases, there may be a decrease in weather-related winter deaths from the same diseases. In the United States, however, our studies suggest that an increase in weather-related deaths in summer would be greater than the decrease in weather-related deaths in winter. To draw firm conclusions, however, this area needs additional study.

- Sudden changes in temperature are correlated with increases in deaths. So if climate variability increases, morbidity and mortality may also increase. Conversely, a decrease in the frequency or intensity of climate extremes may be associated with a decrease in mortality and morbidity.

- Seasonal variation in perinatal mortality and preterm birth (higher in the summers, lower in the winters) have been observed in several areas in the United States. The longer and hotter summers that may accompany climate change could increase infant mortality rates, although changes in variability may be more important than average changes in temperature.

- Vector-borne diseases, such as those carried by ticks, fleas, and mosquitoes, could increase in certain regions and decrease in others. In addition, climate change may alter habitats. For example, some forests may become grasslands, thereby modifying the incidence of vector-borne diseases.

- While uncertainties remain about the magnitude of other effects, climate change could have the following impacts:

  - If some farmland is abandoned or some forests become grasslands, a result could be an increased amount of weeds growing on cultivated land, and a potential increase in the incidence of hay fever and asthma.

  - If humidity increases, the incidence and severity of skin infections and infestations such as ringworm, candidiasis, and scabies may also rise.

  - Increases in the persistence and level of air pollution episodes associated with climate change may have adverse health effects.

CLIMATE-SENSITIVE ASPECTS OF HUMAN HEALTH

Human illness and mortality are linked in many ways to the environment (Figure 12-1). Mortality rates, particularly for the aged and very ill, are

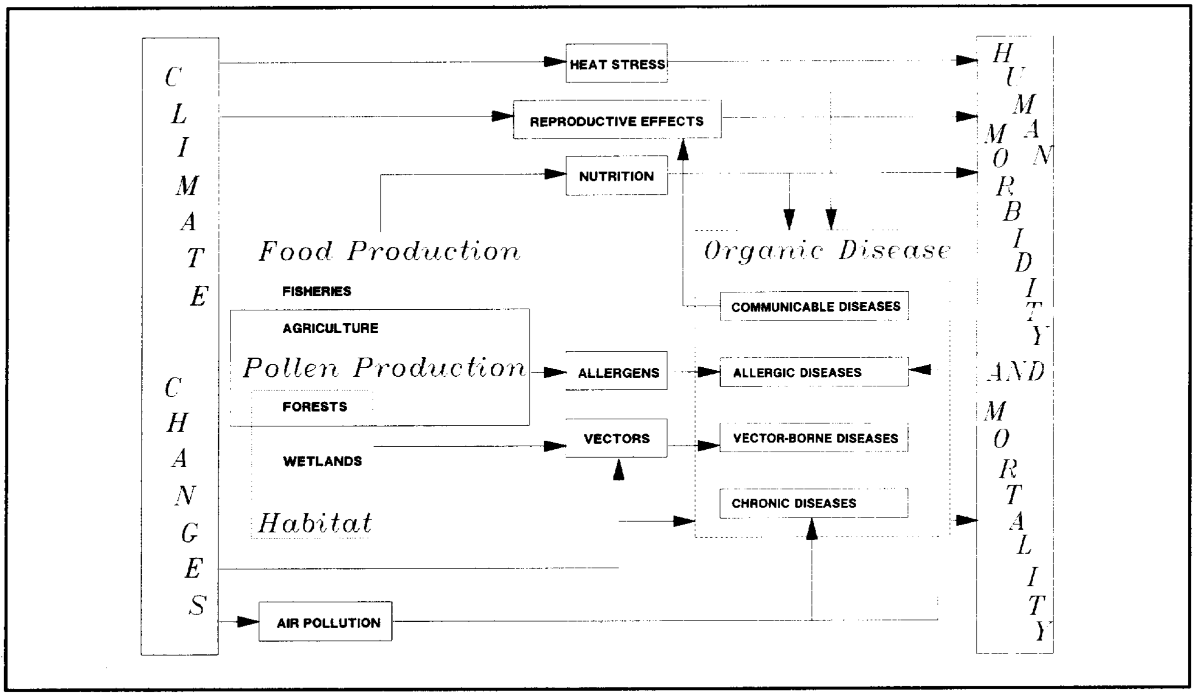

Figure 12-1. Schematic showing how climate change can affect human health.

influenced by the frequency and severity of extreme temperatures. The fife cycles of disease carrying insects, such as mosquitoes and ticks, are affected by changes in temperature and rainfall, as well as by modifications in habitat that result from climate change. Air pollution, frequently associated with climate change, is known to increase the incidence or severity of respiratory diseases such as emphysema and asthma. A variety of human illnesses show sensitivity to the changes in temperature (and/or humidity) that accompany changes in season. Stroke and heart attacks increase with very cold or very warm weather. Allergic diseases such as asthma and hay fever increase in spring and summer when pollens are released. Diseases spread by insects such as St. Louis encephalitis[1]increase in the warmth of summer when the mosquitoes that transmit it are active. In addition, adverse effects on reproduction, such as increased incidence of premature births, show a summertime peak in some cities. Table 121 lists the number of deaths and the number of physician visits (used to estimate the incidence of illness associated with a given effect) associated with major causes of mortality and illness in the United States.

General Mortality and Illness

The relationship between mortality and weather has been studied for over a century (Kutschenreuter, 1959; Kalkstein, Volume G), with the relationship between mortality and temperature receiving the most attention. Kutschenreuter (1959) observed "mortality is higher during cold winters and hot summers and lower during warm winters and cool

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[1] St. Louis encephalitis is an example of a vector-borne disease. Such diseases are spread to humans or animals by arthropods (e.g., mosquitoes or ticks). The disease-causing organism, such as a virus, is carried and transmitted by the vector, also known as the agent. Some vectors, such as ticks, live on other animals, such as deer and birds, which are called intermediate hosts. For example, Lyme disease is caused by a bacteria (the agent), which is carried by a certain type of tick (the vector), which lives on deer and mice (the intermediate hosts).

Table 12-1. Major Causes of Illness and Mortality in the United States (1984)[a]

Causes of illness and mortality	Estimated number of physician contacts	Estimated mortality	
		Number	Rate/100,000
Accidents and adverse effects	70,000,000	93,520	39.6
Cerebrovascular diseases[b]	9,100,000	154,680	65.5
Chronic liver disease and cirrhosis	1,400,000	26,690	11.3
Chronic obstructive pulmonary diseases and allied conditions	20,500,000	70,140	29.7
Congenital abnormalities	4,300,000	12,900	5.5
Diabetes mellitus	35,600,000	35,900	5.2
Heart diseases	72,400,000	763,260	323.2
Malignant neoplasms	20,300,000	453,660	192.1
Pneumonia and influenza	14,500,000	58,800	24.9
Suicides, homicides	---	47,470	20.1
Total for potentially weather-sensitive diseases	152,100,000	1,082,780	448.5
Total for all causes	248,100,000	1,717,020	717.1

[a] Causes are presented in alphabetical order and therefore are not ranked by severity.
[b] Conditions that can be influenced by changes in weather and climate are indicated in **bold type**.
Source: CDC (1986).

summers." The people most sensitive to temperature extremes are the elderly (White and Hertz-Picciotto, 1985). One explanation is the increased susceptibility of the elderly is that for individuals already stressed by the circulatory problems associated with vascular and heart disease, heat waves (temperatures above 100°F for 5 consecutive days) "overload" the thermoregulatory system, which is struggling to maintain the appropriate body temperature. This results in heat stress, heatstroke, and often mortality as well (White and Hertz-Picciotto, 1985).

In addition to the elderly, people working in hot environments, such as steel mills and construction sites, are at special risk from heat waves (Dukes-Dobos, 1981). These workers face even greater risk if they have underlying medical problems such as impaired circulation; higher than normal body temperature due to disease; chronic diseases such as alcoholism, diabetes, and obesity; or other problems.

Cardiovascular, Cerebrovascular, and Respiratory Diseases

Although much of the earlier information characterized the relationship between weather and total mortality from all causes, a growing body of literature evaluates the relationship of weather to specific causes of death. For example, changes in weather have been associated with impacts on the cardiovascular, cerebrovascular, and respiratory systems. As previously shown in Table 12-1, diseases of these three systems cause the majority of deaths observed on a yearly basis in the United States, as well as significant illness. Incidences of these diseases rise as climate extremes increase.

The relationships of weather variables to diseases of these systems are diverse and complicated. Weather is not the main causative factor in these diseases but, rather, changes in weather have an impact because they add stress to systems that have already been compromised for some other reason(s). For example, although it has been observed that deaths in individuals with diseases of the cardiovascular system go up with heat waves, the precise reason for this relationship is not known.

To understand the relationship between weather and these diseases, one must examine the specific diseases that come under broad categories such as "cardiovascular disease." For instance, heart attack, coronary heart disease, and possibly coronary arteriosclerosis and rheumatic heart disease are apparently sensitive to changes in temperature (particularly cold and heat waves), whereas ischemic heart disease is not (Vuori, 1987).

That these different relationships exist is not unexpected given that different parts of the system are compromised (e.g., the arteries in arteriosclerosis and the heart muscle in rheumatic heart disease), and that different causes are also likely (e.g., an infection-related process in rheumatic heart disease and diet and heredity in arteriosclerosis). What this information does indicate, however, is that these relationships are very complex and that unraveling them to predict the effects of global warming will require considerable analysis (Lopez and Salvaggio, 1983).

The relationship between temperature changes and illness (morbidity) from diseases such as heart attack and stroke is not as well defined as the relationship reported for mortality. Mortality has national reporting procedures, whereas morbidity must be estimated from such data as hospital admission figures. A few studies have evaluated the relationship of weather to hospital admissions from cardiovascular or cerebrovascular disease. These have shown a relationship to weather changes, e.g., an increase in admissions for cardiovascular effects with heat waves, similar to that observed for mortality (Sotaniemi et al., 1970; Gill et al., 1988).

Morbidity from respiratory diseases is somewhat easier to estimate, principally because two such diseases, asthma and hay fever, affect as much as 3 and 6% of the U.S. population, respectively, causing significant losses of work time. The most common seasonal pattern for the allergic type of asthma and for hay fever is an increased springtime occurrence in response to grass pollens. A nonseasonal form of allergic asthma may also occur in response to allergens such as molds, which are affected by changes in precipitation and temperature.

Vector-Borne Diseases

Two tick-borne diseases currently posing a public health problem in the United States, Rocky Mountain spotted fever and Lyme disease, induce similar initial symptoms: high fever, chills, headache, backache, and profound fatigue. Rocky Mountain spotted fever can eventually result in hemorrhagic areas that ulcerate, and Lyme disease may cause permanent neurologic, cardiac, and rheumatologic abnormalities (APRA, 1985). The ticks that spread these diseases, and therefore the geographic distribution of the diseases themselves, are affected both directly and indirectly by climate variables. Such environmental factors as temperature, humidity, and vegetation directly affect tick populations and the hosts of the tick populations, e.g., deer, mice, and birds.

Mosquito-borne diseases, such as malaria and certain types of encephalitis (inflammation of the brain), are not a major health problem in the United States today because occurrences are relatively rare. However, mosquitoes are also weather-sensitive insects favoring a warm, humid climate. The spread of mosquito populations and the diseases they carry depends in part upon such climate factors as temperature and humidity, and upon vegetation, which is also influenced by the climate.

Human Reproduction

Preterm delivery and perinatal mortality (i.e., death just before, during, or just after birth) are two adverse reproductive outcomes that are associated with particular seasons and, thus, might be affected by climate change. Statistically significant increases in preterm births and in perinatal mortality in the summer months have been documented (Keller and Nugent, 1983; Copperstock and Wolfe, 1986) (see Figure 12-2). The data on total perinatal deaths correspond closely with those on perinatal deaths associated with infection in the mother or infant, suggesting that the observed seasonality in perinatal death is linked to a seasonality of reproductive infections (Keller and Nugent, 1983).

POTENTIAL HUMAN HEALTH EFFECTS OF CLIMATE CHANGE

To assess the effects of climate change on human health, EPA sponsored three studies for this report (Table 12-2). Longstreth and Wiseman (Volume G) reviewed the literature on the incidence of, and mortality due to, vector-borne diseases. In November 1987, they also conducted a workshop of scientists to evaluate the potential impacts of global climate change on vector-borne infectious diseases in the United States. Following the workshop, Haile (Volume G) conducted modeling studies of the potential impact of climate change on (1) the distribution of the American dog tick, the vector of Rocky Mountain spotted fever; and (2) the potential for malaria transmission in the United States. The third study, by Kalkstein (Volume G), as an extension of an earlier modeling study that assessed the potential effects of global climate change on the elderly and on total mortality in New York (Kalkstein et al., 1986). Kalkstein (Volume G) expanded the New York analysis to include 14 other cities. A detailed review of these three studies, supplemented with other information from the literature, is presented in this section.

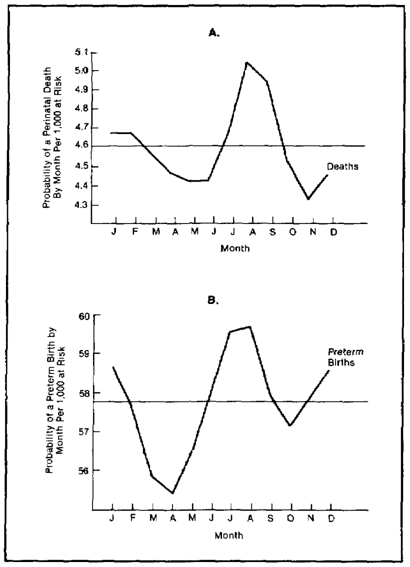

Figure 12-2. Probabilities of (A) perinatal death or (B) preterm delivery (Kelley and Nugent, 1983).

Table 12-2. Studies Conducted for This Report

- The Impact of CO_2 and Trace Gas-Induced Climate Change Upon Human Mortality - Kalkstein, University of Delaware (Volume G)
- Computer Simulation of the Effects of Changes in Weather Pattern on Vector-Borne Disease Transmission - Haile, U.S. Department of Agriculture (Volume G)
- The Potential Impact of Climate Change on Patterns of Infectious Disease in the United States - Longstreth and Wiseman, ICF/ Clement Associates, Inc. (Volume G)

General Mortality

Preliminary analyses suggest that unless the U.S. population becomes fully acclimatized[2] to higher temperatures, climate change will be associated with a sharply rising number of summer deaths. With full acclimatization to the warmer summers, heat-related mortality might increase less dramatically or not at all. In winter, the number of weather-related deaths will probably decline regardless of acclimatization. It is not clear what the net effect of these two offsetting trends may be.

Only a few studies have evaluated the effects of global climate change on human mortality. Kalkstein et al. (1986) developed a regression equation involving nine weather elements, such as temperature, windspeed, and humidity, to give the best algorithm for describing the current impact of weather on mortality. The algorithm used mortality data from New York City for 1964-66, 1972-78, and 1980.

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[2] Estimations of the impact of warming on future mortality must address the question of whether humans will acclimatize (socially, psychologically, or physiologically adapt) to changing weather. How quickly humans may become acclimatized is a topic of considerable controversy, so it is difficult to predict whether the climate changes due to global warming will occur slowly enough to permit acclimatization.

The analysis revealed the existence of a summertime "threshold temperature" -- the maximum temperature above which mortality increases -- for New York City of 92 F for total deaths. This information was then used to assess the potential impact of climate change under the assumption that the population would not acclimatize, as well as under the assumption that it would acclimatize. Unacclimatized impacts were estimated by combining the climate scenarios and the historical weather algorithm described above, and acclimatized impacts were estimated by analyzing analog cities that have values of weather variables today that look like those New York is estimated to have under climate change.

Assuming full acclimatization and a scenario predicting that New York will be 3 to 4°C (5 to 7°F) warmer than it is today, no additional deaths were predicted. However, assuming no acclimatization, the number of summertime deaths attributable to temperatures above the threshold (hereafter called suprathreshold summer deaths) increased seven- to tenfold. Changes in winter weather, i.e., more subthreshold temperatures, were not estimated to affect mortality.

For this report, Kalkstein (Volume G) extended the New York analysis to cover 14 additional metropolitan areas and to evaluate the impact of two climate scenarios: the GISS doubled CO scenario, and the GISS transient A scenario, e4uated at 1994 to 2010 and at 2024 to 2040. Threshold temperatures were calculated for each city for summer and winter. Historical relationships between mortality and temperature were derived independently for each of these 15 cities for both summer and winter. Table 12-3 summarizes the results for total mortality, by city and by season (summer or winter), for the doubled CO_2 scenario with and without acclimatization. The cities with the highest estimated number of suprathreshold summer deaths historically were New York City, Chicago, and Philadelphia; each averaged over 100. All of the cities with the highest average number of summer deaths are in the Midwest or Northeast, and those with the lowest number are in the South.

Table 12-3. Estimated Future Mortality Under Doubled CO_2 Climate Conditions without and with Acclimatization Human Health

City	Number of deaths per season					
	Summer			Winter		
	Current	Without	With	Current	Without	With
Atlanta	18	159	0	2	2	0
Chicago	173	412	835	46	2	96
Cincinnati	42	226	116	14	6	0
Dallas	19	309	179	16	1	0
Detroit	118	592	0	16	2	37
Kansas City	31	60	138	21	5	0
Los Angeles	84	1,654	0	0	0	0
Memphis	20	177	0	0	0	0
Minneapolis	46	142	235	5	1	0
New Orleans	0	0	0	0	0	0
New York	320	1,743	23	56	18	25
Oklahoma City	0	0	47	0	0	0
Philadelphia	145	938	466	10	1	1
St. Louis	113	744	0	47	7	0
San Francisco	27	246	159	10	7	0
Total	1,156	7,402	2,198	243	52	159

Source: Kalkstein (Volume G).

As would be expected, generally more deaths were predicted for populations that do not acclimatize. However, for certain cities, e.g., Chicago, Kansas City, and Minneapolis, more deaths were predicted with acclimatization than without. Exactly why this occurred is uncertain. The results appear to be very sensitive to the choice of the analog city. For example, Chicago appears to have more deaths if its population becomes acclimatized than if it does not. It may be that the analog city chosen to represent a particular acclimatized city, Chicago for instance, is more sensitive to weather effects on mortality than Chicago currently is. More research is planned to investigate this apparent anomaly to refine the estimates of what global warming will mean in terms of mortality. Thus, Kalkstein's results should not be used as predictions of individual city behavior, but as illustrations of sensitivities.

In the absence of any acclimatization, suprathreshold summer mortality in the United Stated under conditions of doubled CO_2 is estimated to rise from an estimated current total of 1,156 deaths to 7,402 deaths, with deaths in the elderly (aged 65 or over) subset contributing about 60% of each figure (727 and 4,605, respectively). Currently, the percentage of elderly in the U.S. population is increasing. Thus, the mortality estimated to result from climate change may be larger than that found by Kalkstein because his analysis is predicated on today's age distribution. Even with full acclimatization, the number of weather-associated summer deaths almost doubles to 2,198, possibly because hot weather increases physiological stress. Kalkstein's analysis also estimates a drop in the number of subthreshold winter deaths. Historically, however, the number of these deaths during the winter in the United States is much smaller (243) than that observed for the summer, and subthreshold winter deaths were estimated to fall to 52 without acclimatization and to 159 with acclimatization. The net result for the United States is an increase in yearly mortality associated with doubled CO_2.

This study is exploratory research in the field of the potential impacts of climate change on human health. Some aspects of the analyses that led to these estimates need further investigation; thus, the estimates should be accepted with caution. The direction of predicted change, i.e., an increase, is probably much more solid than the magnitude of change. In addition, this research has concentrated on mortality occurring above a particular threshold temperature for summer or below a particular threshold temperature for winter. Consideration of a broader range of temperatures could conceivably result in different conclusions being drawn.

Cardiovascular, Cerebrovascular, and Respiratory Diseases

Overall global warming and climate change may exacerbate the effects of cardiovascular, cerebrovascular, and respiratory diseases. Data from these studies show an inverse relationship between mortality and temperature (i.e., deaths go down as temperature goes up) for the range between -5 C and about +25 C, with sharp increases at temperatures above and below this range, particularly for the elderly and for hot weather (White and Hertz-Picciotto, 1985); the exact range appears to depend on the city. Illustrations of this relationship for coronary heart disease and stroke are shown in Figures 12-3 and 12-4, respectively (Rogot and Padgett, 1976). This complex relationship precludes simple prediction of the net effect of climate change. For example, it is possible that hot weather-associated mortality from these diseases may increase in some localities, but this trend may be offset, at least in part, by a decrease in cold weather-associated mortality.

Just as higher summer temperatures are associated with increases in mortality from cardiovascular, cerebrovascular, and respiratory diseases, they are also likely to be associated with increases in morbidity from these diseases through increases in the number or duration of hospital admissions. Particular stress may be put on the respiratory system because climate change can potentially increase pollen, urban smog (discussed below), and heat stress, all of which have an adverse effect on the respiratory system.

For example, if, as has been suggested in the chapter on forests, climate change encourages a transition from forest to grassland in some areas, grass pollens could increase. This, in turn, may increase cases of pollen-induced hay fever and allergic asthma. (However, the switch from forest to grassland would reduce the amount of tree pollens that also cause allergic responses in some individuals.) Rises in humidity also may affect the incidence of mold-induced asthma and hay fever.

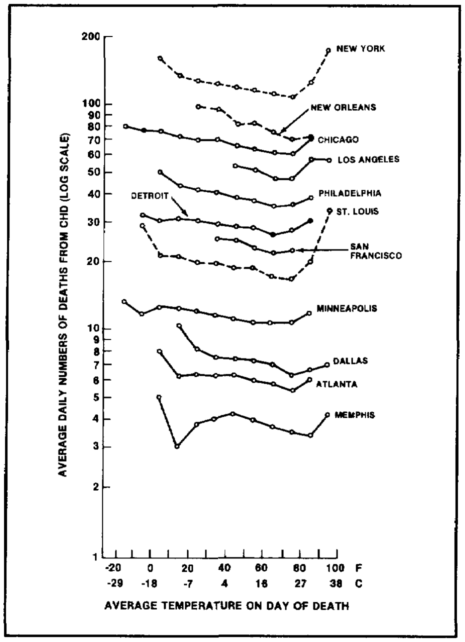

Figure 12-3. Relationship of temperature to heart disease mortality (adapted from Rogot and Padgett, 1976).

As indicated in Chapter 11: Air Quality, global warming may modify global and regional air pollution because it may increase concentrations of ozone and may also have impacts on acid deposition and general oxidant formation. The increasing occurrence of numerous respiratory diseases, such as lung cancer, emphysema, bronchitis, and asthma, has been attributed to the pollutants in urban smog (Lopez and Salvaggio, 1983). Many of the trace gases implicated in global warming contribute to these problems; other pollutants are created from the interaction of ultraviolet light with these and other chemicals present in the atmosphere.

The component that causes the greatest concern in urban smog is ozone (Grant, 1988). If global warming causes an increase in tropospheric ozone, adverse consequences could result for adult asthmatics and people who suffer from acute or chronic bronchitis.

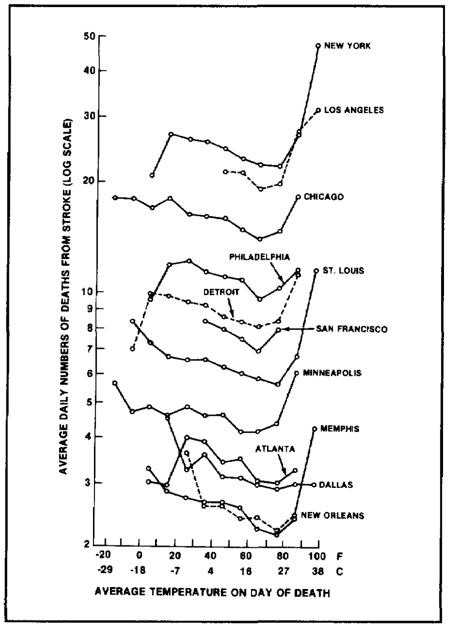

Figure 12-4. Relationship of temperature to mortality from stroke (adapted from Rogot and Padgett, 1976).

Vector-Borne Diseases

Potential changes in humidity and temperature could alter the geographic ranges and life cycles of plants, animals, insects, bacteria, and viruses. (For further discussion of forestry and agriculture, see Chapters 5 and 6, respectively.) For example, the range of many plant pests may move northward by several hundred miles. Such changes could occur for insects that spread diseases to both humans and animals. Vector-borne diseases that affect humans are relatively rare in the United States. The incidence of most of those found, however, is increasing. The incidence of some, such as Lyme disease, is increasing dramatically (CDC, 1986).

Tick-Borne Diseases

Both Rocky Mountain spotted fever and Lyme disease are considered to be public health problems in the United States. Although these two diseases are spread by different species of ticks, some overlap exists in their geographic distribution (Figure 12-5). Because tick populations appear to be limited by the size of their intermediate host populations (such as white-tailed deer), the spread of tick-borne diseases may be particularly sensitive to any change that may affect the geographic range of these hosts and, consequently, the range of the vector, or carrier.

In addition to the presence of the host, tick populations also depend upon the seasonality of environmental factors such as temperature, humidity, and vegetation. Optimally, climate must be warm enough to promote progression through the life cycles, humid enough to prevent the drying out of eggs, and cold enough in winter to initiate the resting stage.

As for many tick-borne diseases, the opportunity for a tick to acquire the infective agent from an infected animal is limited to the short period when the level of the agent in the blood of the host is high enough for the tick to receive an infective dose. Higher temperatures may increase the amount of the agent (the organism that is transmitted by the carrier, such as a virus) and the time it remains lodged on the host animal. Both these mechanisms would increase the rate of infection of the carrier. However, although higher temperatures may favor the presence of the agent, there is some indication that they could disrupt the life cycle of some tick species. In these cases, warmer temperatures would reduce both tick survival and the spread of diseases they carry.

Tick populations also vary with the natural vegetation of an area. The incidence of Rocky Mountain spotted fever, in particular, has been linked to natural vegetation and changes in climate.

In examining the potential impact of climate change in the United States on Rocky Mountain spotted fever, Haile (Volume G) used a weatherbased model, ATSIM, to evaluate the impact of the scenario climate changes on the distribution of the American dog tick, the primary carrier of this disease (Haile, Volume G; Mount and Haile, 1988). The model uses data inputs from the three doubled CO_2 scenarios (GISS, GFDL, and OSU) to estimate population dynamics, growth rate, and generation time. Haile assumed that habitats and host density did not change in response to global warming. Sample results for six cities representing the most southern, the most northern, and the two middle latitudes are presented in Figure 12-6. The results indicate that under all scenarios, tick populations would shift from south to north and would be virtually eliminated from the most southern locations (Jacksonville and San Antonio). However, in the middle latitude cities, the results are mixed and depend on the scenario evaluated. The model does not estimate changes in incidence of the disease.

In this analysis, the only model inputs that were changed to simulate climate change were the weather inputs. Other important parameters in the model are the distribution of habitat between forests and meadows and the presence of suitable hosts. Both parameters are likely to be changed relative to current conditions under climate change. As indicated in Chapter 5: Forests, a change from forests to meadows may occur in certain areas of the country; this would depress the tick population. However, the distribution of small mammals also may change. If small mammal populations increased, tick populations would grow. In addition, this study did not consider changes in climate variability, which may have a major effect on the outbreak of diseases.

In a sensitivity analysis of their model, Mount and Haile (1988) found that the model predictions could vary sixteenfold, depending on the inputs used for host density, whereas the variability conferred by changes in the weather inputs is about fourfold. Based on the sensitivity analysis, host densities are extremely important to these predictions. Keeping them constant, as was done in this analysis, could have underestimated or overestimated the impact of climate change on the density of the American dog tick.

Mosquito-Borne Diseases

A second category of vector-borne diseases that can be affected by climate change consists of diseases carried by mosquitoes. Climate changes resulting in more days between 16 and 35 C (61 to 95 F), with humidity between 25 and 60%, are likely to favor the growth of mosquitoes (White and Hertz-Picciotto, 1985). Mosquito populations are also sensitive to the presence of standing water. It is not clear whether standing water will generally increase or decrease (see Chapter 9: Water Resources). Worldwide, mosquito-borne diseases are associated with significant illness and mortality. In the United States, however, vector control programs and improved hygiene have virtually eliminated endogenously transmitted cases of these diseases, with the exception of sporadic outbreaks of arbovirus-encephalitis. (Imported cases are seen occasionally.) Numerous mosquito species are present

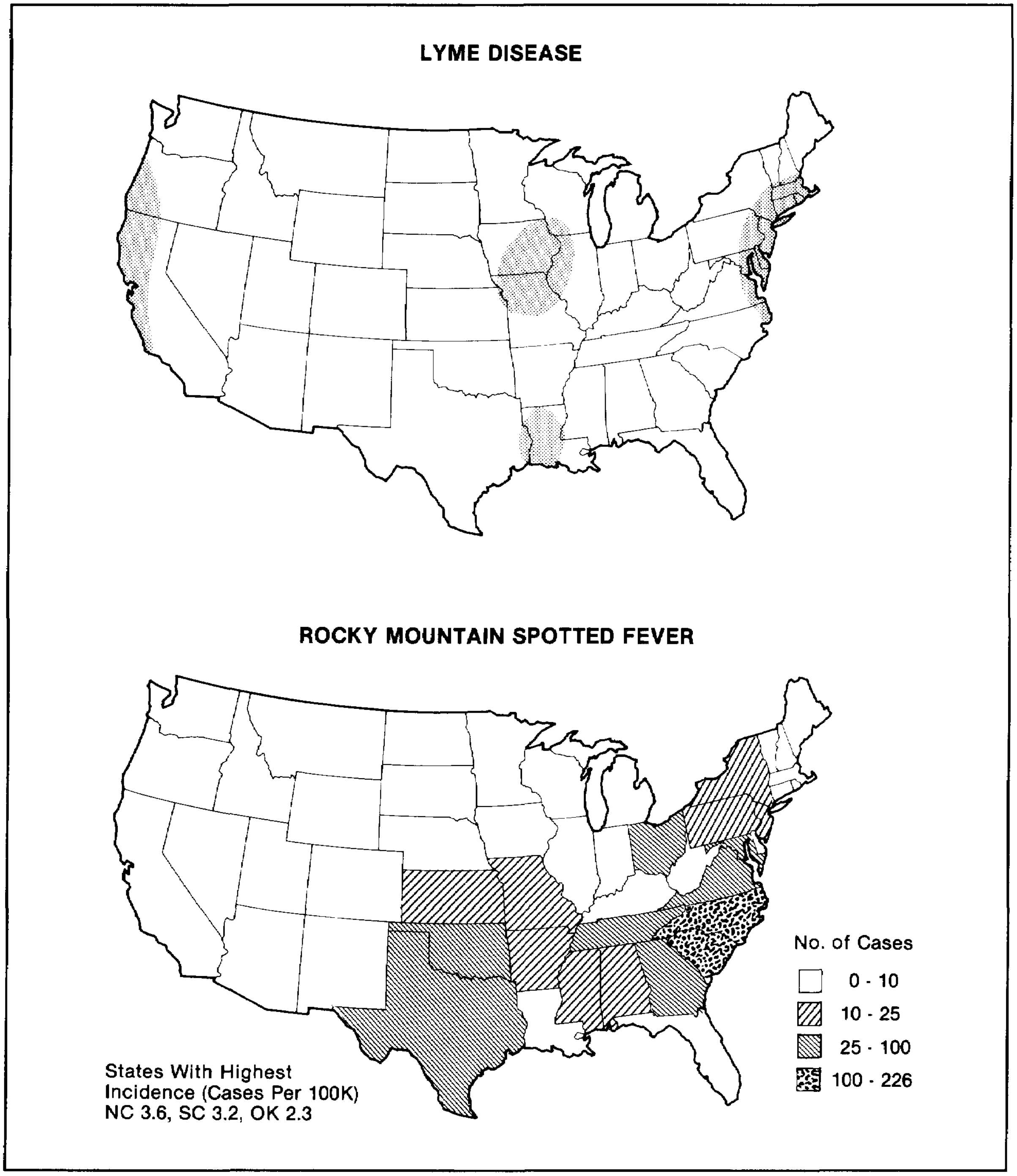

Figure 12-5. Geographic distribution of Lyme disease and Rocky Mountain spotted fever (Longstreth and Wiseman, Volume G).

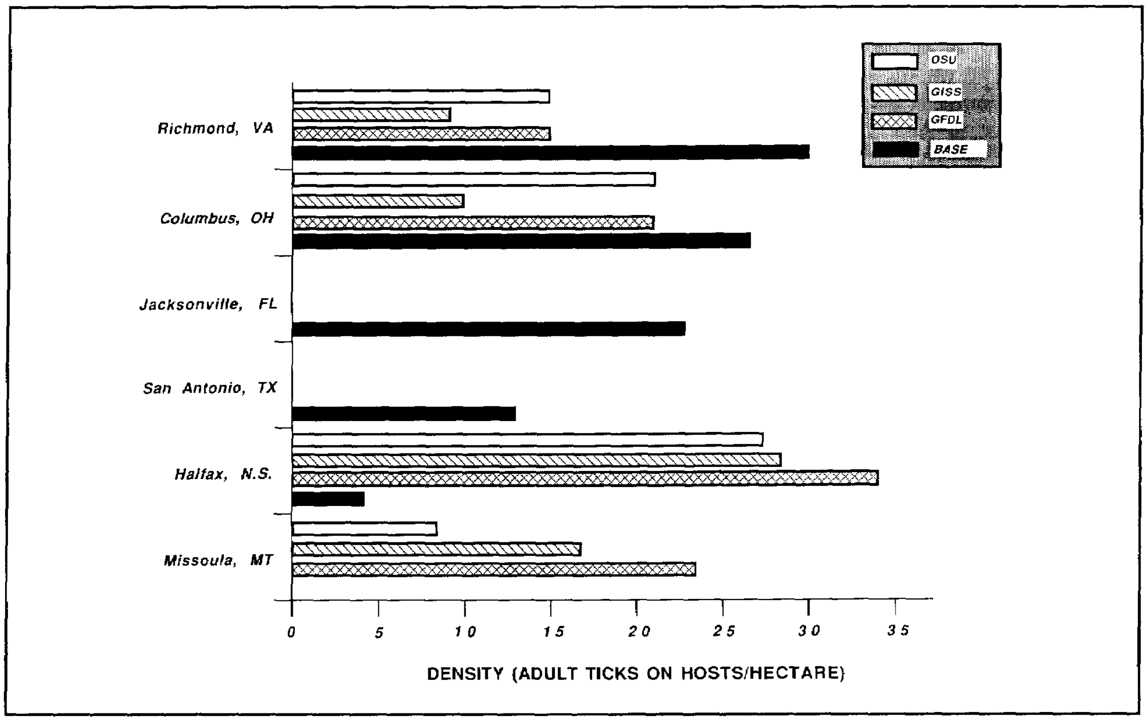

Figure 12-6. Simulated tick densities for selected cities under various scenarios of climate change (Haile, Volume G).

in the United States, however. Recent restrictions on pesticide use, coupled with the influx of visitors and immigrants who can serve as sources of infectious agents, as well as the lack of available vaccines for many of the potential diseases, suggest the potential for reintroduction and establishment of these diseases in the United States -- particularly if global warming provides a more suitable climate for their growth and development (Longstreth and Wiseman, Volume G).

At a recent workshop, five of the numerous mosquito-borne diseases were considered to pose a potential risk to U.S. populations if the status quo is disturbed by climate change (Longstreth and Wiseman, Volume G). Malaria, dengue fever, and arbovirus-induced encephalitides were considered to be significant risks, and yellow fever and Rift Valley fever were considered to be possible risks.

Malaria

Malaria is an infectious disease transmitted by mosquitoes and induced by parasites (Plasmodia). The symptoms are highly variable, depending on the species of the agent. They include chills, sweats, and headache, and in severe cases, may progress to liver damage and even liver and renal failure.

As a result of effective vector control and treatment programs, malaria is no longer indigenous to the United States. However, imported cases occur regularly, and occasionally indigenous transmission has been documented (Longstreth and Wiseman, Volume G). Current U.S. demographic trends, including a large number of legal and illegal immigrants from locations where malaria is endemic, could present a pool of infected individuals that, in conjunction with climate changes, may create sufficient conditions for increased disease incidence.

Haile used the weather-dependent model MALSIM to evaluate the potential impact of climate change on malaria in an infected population living in an area where a competent carrier is present. The model was originally developed to help predict malaria outbreaks in tropical countries such as Kenya. This is

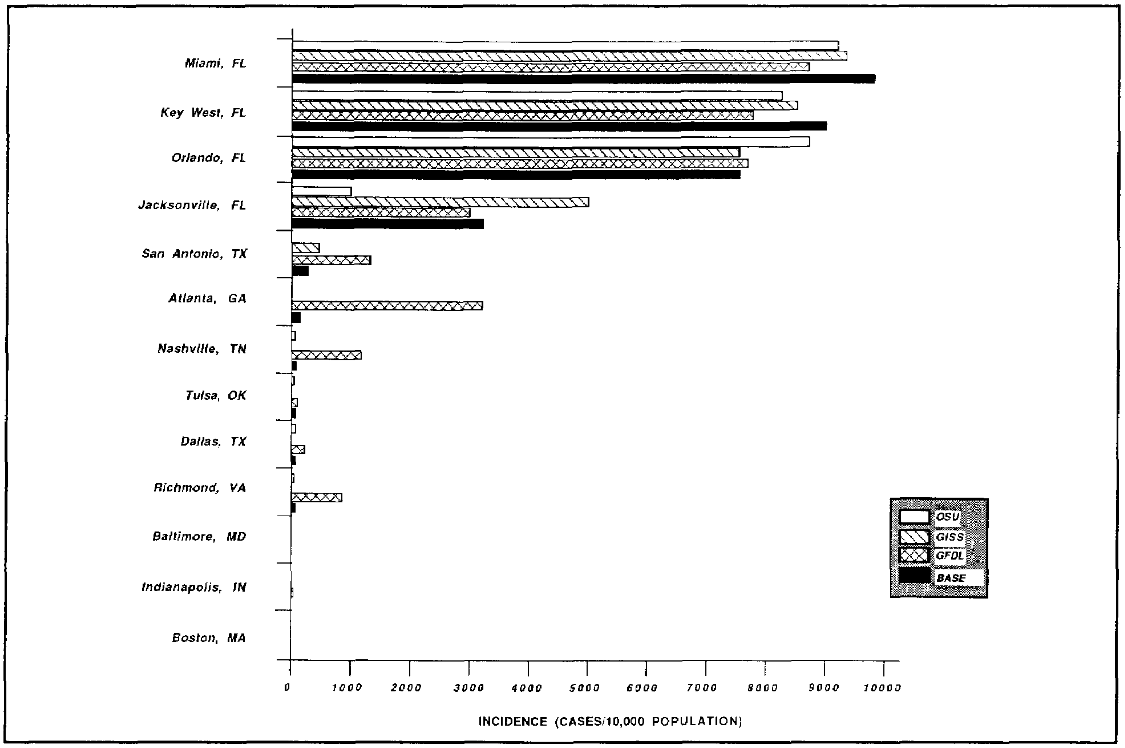

Figure 12-7. Simulated incidence of malaria for selected cities under various scenarios of climate change (Haile, Volume G).

the first application of the model to the United States. This analysis did not consider changes in climate variability, which may be important for the spread of malaria. The MALSIM model showed that several cities in the South (e.g., Miami, Key West, and Orlando), under current climate conditions, are very favorable for malaria transmission.[3] Using the climate change scenarios in MALSIM did little to affect the estimated transmission potential of malaria in the United States (Figure 12-7). In a few cities, e.g., Richmond, Nashville, and Atlanta, the model estimated large increases in one scenario relative to those that would occur normally. However, the results varied with different climate scenarios, did not occur at all locations, and should be considered to be inconclusive.

Dengue Fever

Dengue fever is an arbovirus-induced[4] illness characterized by fever, rash, and severe pain in the joints. The dengue virus has four different types (DEN 1 through DEN 4). Sequential infection by different types is possible and has been suggested to lead to an increased risk of developing a more severe, hemorrhagic form of the disease that can be fatal in the very young and the elderly. Like malaria, it is not

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[3] The MALSIM estimates of malaria incidence by city under current conditions were based on two assumptions: that there were 100,000 female mosquitoes in the vicinity of each city and that 100 infected people were added to the cities' populations. Under those assumptions, infection of virtually the entire population of Miami was predicted to be possible unless protective measures were taken.

[4] An arbovirus is a virus transmitted by an arthropod. Arthropods are a group of animals that includes insects and arachnids. Examples of arthropods that transmit disease include mosquitoes and ticks.

currently endemic in the United States, although potential carriers are present and the disease is imported here regularly by people who have traveled abroad.

The ability of the vector to transmit the agent appears to depend on temperature, and current conditions do not appear to be favorable for this process. Climate changes that raise temperatures, however, may reduce the required incubation period and increase the infectivity of the carrier, increasing the potential transmission of the disease.

Arbovirus-Related Encephalilides

Arbovirus-related encephalitides are a group of acute inflammatory diseases that involve parts of the brain, spinal cord, and meninges. In mild cases, these infections result in feverish headaches or aseptic meningitis; in more severe cases, those symptoms can be accompanied by stupor, coma, convulsions (in infants), and occasionally spastic paralysis (APRA, 1985).

At least seven types of viruses causing encephalitis are present in the United States. These include the three forms that also infect horses (the western, eastern, and Venezuelan equine encephalitis viruses) as well as four that are named after the location of their discovery (the La Cross, St. Louis, Powassan, and California encephalitis viruses). Cases range in severity depending on the type of virus, with yearly fatality rates between 0.3 and 60%. These infections are rare. In 1984, 129 cases were reported to the Centers for Disease Control, which maintains an active surveillance program for them (CDC, 1986).

Outbreaks of encephalitis attributable to these viruses are normally limited to specific geographic locations and seasons for several reasons. First, warm temperatures are normally required for the viruses to multiply and to be transmitted to a new host. Higher temperatures may quicken the transmission process and promote epidemic disease. However, the extent of this effect depends largely on the particular virus. Some viruses require cooler weather and higher moisture conditions. Thus, higher temperatures may reduce their prevalence. Second, environmental conditions that favor the presence of carriers and hosts must prevail. For example, relative humidity may affect plant life necessary for the feeding of hosts.

Other Diseases

The incidence of a variety of other U.S. diseases appears to be sensitive to changes in weather. If humidity is higher, an increased incidence and severity of fungal skin diseases (such as ringworm and athlete's foot) and yeast infections (such as candidiasis) may be observed. Studies on soldiers stationed in Vietnam during the war indicated that outpatient visits for skin diseases (the largest single cause of outpatient visits) were directly correlated to increases in humidity but showed a 4-month lag with relationship to temperature increases (Figure 12-8). In addition, excessively high temperatures can lead to such skin diseases as prickly heat and heat rash, which impair the ability of the skin to breathe and thus place additional stress on people already suffering from overexposure to heat from other causes.

Several diseases appear to be associated with the acquisition of winter infections. If a reduction in winter severity is also accompanied by a decrease in wintertime infections, these diseases could be reduced under global warming.

For example, birth in cold winter months has been associated with a higher risk of schizophrenia in individuals whose schizophrenia is without an apparent genetic component (Kovelman and Scheibel, 1983). In addition, juvenile-onset diabetes, which has been reported to be increasing over the past several decades, has been shown to be associated with a seasonal variation in that the month of first admission peaks in the winter (Glatthaar et al., 1988; Patterson et al., 1988). It is a common clinical experience that a minor viral illness precedes the onset of symptoms.

SOCIAL AND ECONOMIC IMPLICATIONS

Demographic and technological trends (the aging of the population, an influx of immigrants, advances in treatment techniques) make it difficult to analyze the potential impacts of climate change on human health. Although this chapter attempts to identify those human health effects at risk from climate change, the analyses were not designed to consider adaptive responses and should not be treated as predictions of what will happen with climate change but as illustrations of sensitivities. Rather, the analyses

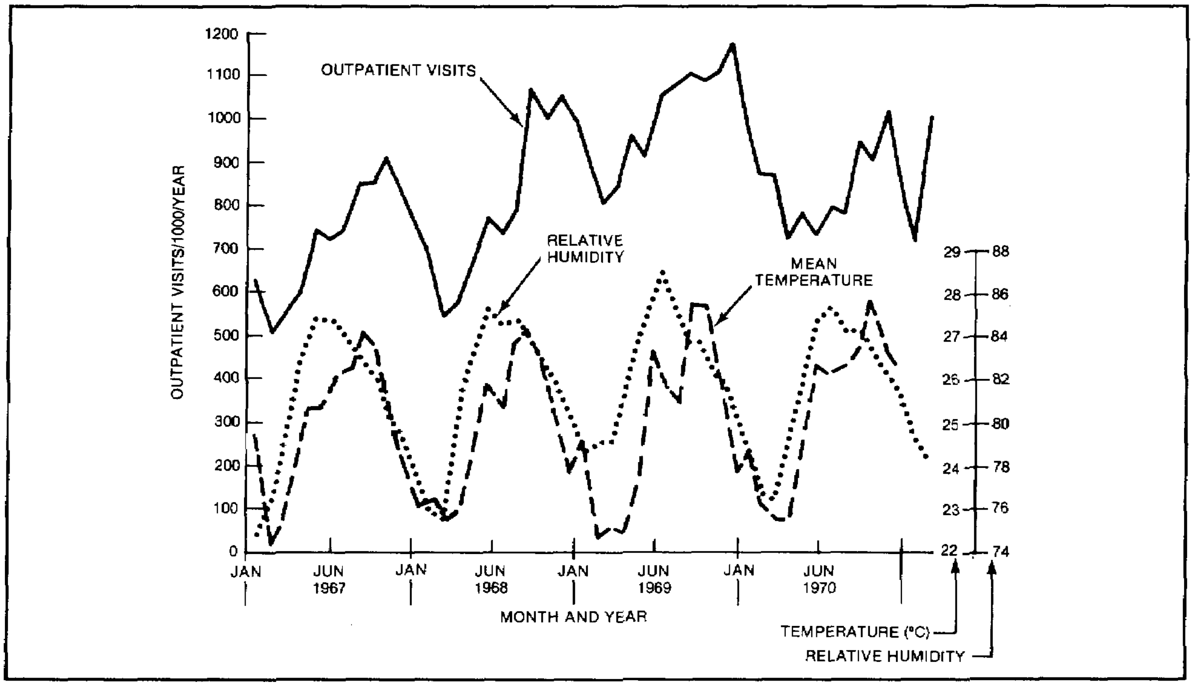

Figure 12-8. Relationship of skin infections to humidity and temperature (Longstreth and Wiseman, Volume G).

presented here represent possible scenarios, in the absence of consideration of demographic trends or adaptive responses, that may either exacerbate or ameliorate the impact of climate change on human health. Societies possess considerable ability to adapt to change. The potential for climate to affect human health may be considerably modified by adaptive responses, such as immunizations, modification of the environmental temperature (e.g., use of air conditioners), and control of disease carriers.

Climate change may affect regional and national health care. For instance, the treatment requirements for asthma may increase or decrease as locations experience changes in the distribution and intensity of pollen concentrations. Increased resources may be needed to treat premature infants if the number of preterm births increases. If heart attacks, stroke, and respiratory problems increase, hospitalization costs and costs due to days lost from work may also increase. Higher health care costs might be particularly obvious in Medicaid and Medicare because those below the poverty line would be less able to take adaptive measures (e.g., air-conditioning), and the elderly are more susceptible to the ill effects of extreme weather conditions.

The United States is already experiencing an infant mortality higher than that of any other industrialized nation (World Bank, 1987). Some studies have found that perinatal mortality is higher in the summer; consequently, the increased temperatures expected with global warming may well exacerbate infant mortality (or at least neonatal mortality).

The need for irrigation may increase in many regions of the United States (see Chapter 6: Agriculture). Irrigation may result in greater amounts of standing water and can therefore increase mosquito populations. Arbovirus encephalitis may become a greater problem than at present, and other mosquito-borne diseases, such as dengue or yellow fever, could be more easily spread if introduced.

One health impact of climate change not assessed in this report is the morbidity and mortality associated with certain kinds of extreme events, e.g., tornadoes and hurricanes. These currently cause some mortality in the United States; however, it is difficult to say whether there will be a change in the mortality induced by these events with global warming. As indicated in Chapter 3: Variability, changes in the frequency of such extreme events cannot be predicted on the basis of an analysis of the general circulation model (GCM) output, although an increase in severity of some kinds of storms, e.g., hurricanes, is not inconsistent with current theories and more detailed models of storm behavior.

The impact of global change on human health will most likely be greater in the lesser-developed countries (LDCs) that do not have the resources to take the adaptive or preventative measures available to the United States. Impacts on agriculture and water resources in the LDCs could result in poor nutrition and water shortages that may make populations more susceptible to disease. Changes in insect (arthropod) habitats may allow diseases to flourish where they never have before. Changes in extreme events such as monsoons or floods could significantly affect mortality in the developing world. Such external impacts on health might have an impact on the United States not only via the potential for introduction of diseases already discussed but also via our participation in international aid and relief programs.

POLICY IMPLICATIONS

The full impacts of climate change on human health will require more research. Agencies such as the Department of Health and Human Services should consider conducting studies on potential impact.

In the future, a cadre of trained professionals may be needed to respond to outbreaks of diseases. A shift in the distribution of carriers of human disease may necessitate regional shifts in surveillance and eradication programs. States that do not have these programs may need to develop them.

RESEARCH NEEDS

Although information evaluating the relationship of weather and season to various health effects is plentiful, research into the significance of these relationships in the context of global warming is scarce. A number of areas requiring further research are described below.

A number of studies have identified relationships between temperature changes and mortality from diseases of the heart, respiratory system, and cerebrovascular system. These studies show slightly different relationships depending on the city that provided the data, although some common elements exist. A statistical analysis of this information might be warranted to determine if one general relationship (across the United States, or perhaps related to latitude) could be developed for each of these categories. Such a relationship could then be used to estimate the impact of global warming by specific disease category.

A companion study to that proposed above should identify the top 10 causes of deaths associated with changes in weather in the Kalkstein study. The results could then be compared with the information derived above to determine other causes of mortality that show great sensitivity to the weather.

The Kalkstein analysis did not look at deaths occurring in the very young (aged 1 year and below). Given the seasonality of perinatal mortality and preterm death observed in several studies, an investigation of the relationship between temperature and mortality in the very young probably would be worthwhile. More baseline information is needed for the latter study. Related studies on perinatal mortality could examine the following:

- Whether the South has a higher per capita incidence of perinatal mortality.
- Whether infections, which have been suggested as a potential cause of the perinatal mortality observed, show a seasonality in parallel to perinatal mortality, and whether more such infections occur in the South.
- The principal causes (e.g., bacteria, viruses) for perinatal infections, and whether they are the same as those for skin infections, and whether they are the same as those for skin infections that increase with increases in humidity.
- Whether the incidence of preterm birth or perinatal mortality is related to weather parameters such as temperature, humidity, or high-pressure systems.

The following additional research areas are suggested:

- Synergism between stratospheric ozone depletion (due to increases in UV-B radiation) and global warming. Increased UV-B radiation and global warming might be expected to exacerbate infectious diseases. UV-B radiation may have an impact on the ability of an individual to respond to a disease, and global warming may change the incidence of certain infectious diseases. For example, leishmaniasis is an important disease in many African countries. In animal models, UV-B irradiation adversely affects the development of immunity to Leishmania. If climate change creates more favorable habitats for the sand-fly vector of this disease, then a double insult to the system could occur: a higher incidence, and a worse prognosis.

- The impacts on LDCs. The Agency for International Development is supporting the development of a Famine Early Warning System (FEWS) that will use a variety of inputs (many of them weather related) to help predict when conditions leading to famine may be occurring. Appropriate GCM outputs could be input into this system to evaluate how the changes associated with global warming may affect famine development. Similarly, the Department of Defense is using a number of models comparable to those used by Haile to attempt to predict where infectious diseases are likely to pose problems for U.S. troops. It might be interesting to evaluate how the climate variables from the GCM-generated scenarios would affect these predictions, particularly in the LDCs where these diseases present a very real problem to the health care systems.

- Introduction of infectious diseases into the United States via immigrants. Anecdotal information indicates that many immigrants are not served by the health care system; consequently, they could become a population where diseases might develop into full-blown epidemics before initiation of treatment. Determining whether or not global warming will affect this process, either directly via the provision of a more hospitable environment for the disease or indirectly via an increased number of immigrants and refugees, will require a better characterization of the current situation.

- Intermediate hosts and their habitats. In the models used by Haile, two important input parameters that were held constant were the size of the intermediate host population and the distribution of habitat between forest and meadow. It is likely that both of these parameters will themselves be affected by climate change. A better grasp of how climate change will affect these parameters needs to be developed and integrated into the infectious disease models.

- Irrigation and incidence of vector-borne disease. An increase in irrigation is possible, which could have a significant impact on mosquito development and therefore on mosquito-borne diseases. The importance of such water is timedependent, however (i.e., it must occur at the right moment in the insect's lifecycle). Thus an analysis of how the growing season overlaps transmission of diseases such as La Cross encephalitis might provide an indication of whether changes in irrigation practices should be a concern in terms of public health.

- Mortality from extreme events. Another issue that might warrant investigation is how climate change may affect the mortality associated with extreme events, such as hurricanes and floods.

- Air pollution and respiratory disease. Air pollution is already a major contributing factor in the incidence and severity of respiratory disease in the United States. An analysis of the extent that global warming will exacerbate air pollution is critical to an assessment of the potential health effects of climate change.

REFERENCES

APRA. 1985. American Public Health Association. In: Berenson, A.S., ed. Control of Communicable Diseases in Man. Springfield, VA: John D. Lucas Printing Company.

CDC. 1986. Centers for Disease Control. Annual

Summary 1984. MMWR 33:54.

Cooperstock, M., and RA. Wolfe. 1986. Seasonality of preterm birth in the collaborative perinatal project: demographic factors. American Journal of Epidemiology 124:234-41.

Dukes-Dobos, F., 1981. Hazards of heat exposure. Scandinavian Journal of Work and Environmental Health 73-83.

Gill, J.S., P. Davies, S.K. Gill, and D.G. Beevers. 1988. Wind-chill and the seasonal variation of cerebrovascular disease.
Journal of Clinical Epidemiology 41:225-230.

Glatthaar, C., P. Whittall, T. Welborn, M. Giboon, B. Brooks, M.M. Ryan, and G. Byrne. 1988. Diabetes in Western Australian children: descriptive epidemiology. Medical Journal of Australia 148:117-123.

Glenzen, W.P. 1982. Serious illness and mortality associated with influenza epidemics. Epidemiological Reviews 4:25-44.

Grant, L.D. 1988. Health effects issues associated with regional and global air pollution problems. Prepared for World Conference on the Changing Atmosphere, Toronto. Draft document.

Harris, R.E., F.E. Harrell, K.D. Patil, and R. AlRashid. 1987. The seasonal risk of pediatric/juvenile acute lymphocytic leukemia in the Unites States. Journal of Chronic Diseases 40:915-923.

Kalkstein, L.S., R.E. Davis, JA. Skindlov, and K.M. Valimont. 1986. The impact of human-induced climate warming upon human mortality: a New York case study. Proceedings of the International Conference on Health and Environmental Effects of Ozone Modification and Climate Change, Washington, DC; June.

Kalkstein, L.S., and K.M. Valimont. 1987. Effect on human health. In: Tirpak, D., ed. Potential Effects of Future Climate Changes on Forest and Vegetation, Agriculture, Water Resources, and Human Health, Vol. V, pp. 122-152. Washington, DC: U.S. Environmental Protection Agency. EPA 400/1-87/101E.

Keller, CA., and R.P. Nugent. 1983. Seasonal patterns in perinatal mortality and preterm delivery. American Journal of Epidemiology 118:689-98.

Kovelman, J., and A. Scheibel. 1986. Biological substrates of schizophrenia. Acta Neurologica Scandinavica 73:1-32.

Kutschenreuter, P.H. 1959. A study of the effect of weather on mortality. New York Academy of Sciences 22:126-138.

Lopez, M., and J.E. Salvaggio. 1983. Climate weather-air pollution. In: Middleton, E., and C.E. Reed, eds. Allergy, Chapter 54. St. Louis, MO: C.V. Mosby Company.

Mount, G.A., and D.G. Haile. 1988. Computer simulation of population dynamics of the American dog tick, Dermacentor variabilis (Acari: ixodidae). Journal of Medical Entomology. In press.

Patterson, C., P. Smith, J. Webb, M. Heasman, and J. Mann. 1988. Geographical variation in the incidence of diabetes mellitus in Scottish children during the period 1977-1983. Diabetic Medicine 5:160-165.

Rogot, E., and S.J. Padgett. 1976. Associations of coronary and stroke mortality with temperature and snowfall in selected areas of the United States 19621966. American Journal of Epidemiology 103:565575.

Sontaniemi, E., U. Vuopala, E. Huhta, and J. Takkunem. 1970. Effect of temperature on hospital admissions for myocardial infarction in a subarctic area. British Medical Journal 4:150-1.

Vuori, I. 1987. The heart and the cold. Annals of Clinical Research 19:156-162.

White, M.R., and I. Hertz-Picciotto. 1985. Human health: analysis of climate related to health. In: White, M.R., ed. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests, and Human Health. Washington, DC: Department of Energy. DOE/ER/0236.

World Bank. 1987. World Development Report 1987. New York: Oxford University Press.

CHAPTER 13
URBAN INFRASTRUCTURE

FINDINGS

Global climate change could require U.S. cities to make major changes in capital investments and operating budgets. Areas most likely to be affected include water supplies, roads, and bridges; storm sewers and flood control levees; and energy demand in municipal buildings and schools.

- Most urban infrastructure in the United States will turn over in the next 35 to 50 years. If potential changes in climate are considered, this turnover will allow cities to prepare for climate change at lower costs. In some cases, the risk of climate change should be incorporated into decisions beginning today, such as coastal drainage systems that are likely to last for 50 to 100 years.

Northern and Southern Cities

- Northern cities, such as Cleveland, may incur a change in the mix of their expenditures. In such locations, increased electricity costs for air-conditioning could be offset by reductions in expenditures for heating fuel, snow and ice control, and road maintenance. Southern cities could see increases in operating budgets due to the demand for additional air conditioning.

Coastal Cities

- Coastal cities, including 12 of the 20 largest metropolitan areas, may face somewhat larger impacts, such as the following:
    - Sea level rise or more frequent droughts would increase the salinity of shallow coastal aquifers and tidal surface waters. Cities that rely on water from these sources should examine water supply options. Such areas as Dade County, Florida, or New York City would probably be vulnerable.
    - As sea level rises, some coastal cities would require levees to hold back the sea or fill to raise the land surface area. In the case of Miami, the cost of these activities might exceed $500 million over the next 50 to 75 years, necessitating an average increase of 1 to 2% in annual capital spending in Greater Miami.

Water Supply and Demand

- Climate change will influence the supply and demand for water in many cities. A lengthened summer season and higher temperatures would increase the use of water for air conditioners, lawns, and gardens. Changes in rainfall patterns, runoff, and flood control measures may alter water supplies. In the Hudson River Basin, summer water demand could increase by 5% over the demand for water without climate change, while supplies might fall. Such a change would require new institutional and management approaches for both the Delaware and Hudson Rivers.

Policy Implications

- Climate change has implications for many national programs and policies, including the following:
    - The National Flood Insurance Program may react to climate change by redrawing floodplain maps and adjusting insurance rates to account for sea level rise and changes in riverflows. This program might consider discouraging development that would be vulnerable to sea level

rise.

- Because of the key role federal programs play in the development of cities, the Department of Housing and Urban Development should examine the implications of climate change on long-term policies. A minimum response might be to provide guidance on the certainties and uncertainties of climate change to groups such as the National League of Cities, the U.S. Conference of Mayors, and the American Planning Association.

- Because water supply infrastructure may last several centuries improved planning is important. The U.S. Geological Survey should study the probable impacts of global climate change and sea level rise on the water supplies of major cities. The U.S. Army Corps of Engineers should factor climate change into the design of major projects.

- Given the assumption that modest changes in the design and location of many transportation systems may facilitate an accommodation to climate change, the Department of Transportation should factor climate change into the design of roads, bridges, and mass transit facilities.

- Voluntary standards organizations, such as the American Society of Civil Engineers, the Building Officials and the Code Administrators International, and the American Society of Heating and Refrigerating and Air Conditioning Engineers should examine the need for changes in existing energy and safety factors to account for the possibility of climate change.

RELATIONSHIP BETWEEN URBAN INFRASTRUCTURE AND CLIMATE

Three-quarters of the U.S. population is concentrated in urban areas (Statistical Abstract, 1988). The majority of the nation's investment in water supply, wastewater transport and treatment facilities, drainage, roadways, airports, mass transit, electric power, solid waste disposal sites, and public buildings serves these urban areas. The current value of selected infrastructure nationwide, displayed in Table 13-1, provides insight into the aggregate investment at stake if climate changes. Most of these items could be considered part of urban infrastructure; their locations and designs have been based on historic meteorologic information. Annually, governments add an average of $4S billion to the capital stock (National Council on Public Works Improvement, 1988).

Of the 20 most populated U.S. urban areas, 18 have access to oceans, major lakes, or rivers and have invested in infrastructure for port facilities and flood control.[1] The expenditure required to construct coastal defense structures – which prevent inundation by the sea, slow oceanfront erosion, control storm surges, slow saltwater advance up rivers, and reduce saltwater intrusion into aquifers – is now minimal.

Although actual practice varies, the nominal replacement cycle for most infrastructure is 35 to 50 years (National Council on Public Works Improvement, 1988). Some water supply investments have 100-year cycles between planned replacement; however, sea level rise, temperature change, and changes in precipitation patterns could alter the balance between water supply and demand. The nature and pattern of precipitation could affect drainage requirements as well as highway design and maintenance.

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[1] Of the 20 most populated urban areas in the United States, 12 are tidal waterfront cities (Baltimore, Boston, Houston, Los Angeles, Miami, New York, Philadelphia/Wilmington, San Francisco/Oakland, San Diego, Seattle, Tampa/St. Petersburg, and Washington, DC), 3 are located on the Great Lakes (Chicago, Cleveland, and Detroit), 3 are on navigable rivers (Minneapolis, Pittsburgh, and St. Louis) and 2 are not on a navigable waterway (Atlanta and Dallas).

Table 13-1. Value of the Nation's Stock of Selected Infrastructure (billions of 1984 dollars)

Component	Value[a]
Water supply	$108
Wastewater	136
Urban drainage	60
Streets	470
Public airports	31
Mass transit	34
Electric power (private only)[b]	266
Public buildings	unknown
Total	$1,105+

[a] Based on a useful life of 35 to 50 years for most assets, and 10 to 20 years for transit vehicles.

[b] About 77% of electric power is privately produced.

Source: Statistical Abstract (1988); National Council of Public Works Improvement (1988).

The heat wave of 1988 illustrated some of the potential impacts. Hundred-degree weather distorted railroad tracks, forcing Amtrak to cut speeds from 200 to 128 kilometers per hour between Washington and Philadelphia (Bruske, 1988) and possibly contributing to a train wreck that injured 160 people on a Chicago-Seattle run (The Washington Post, 1988). A U.S. Army Corps of Engineers contractor worked around the clock for 2 weeks to build a 170-meter-wide, 9-meter-high silt wall across the bottom 40% of the Mississippi River channel, 48 kilometers below New Orleans (Sossaman, 1988a,b). This $2 million wall, designed to wash away when spring snowmelt demands the full capacity of the channel, slowed an advancing wedge of saltwater that threatened the water supply in New Orleans and nearby parishes. In Manhattan, heat exacerbated the effects of longstanding leaks in 256 kilometers of steam pipes, causing the asphalt to soften. As vehicles kneaded the soft asphalt, thousands of bumps formed on city streets, requiring extensive repairs (Hirsch, 1988). In the suburbs of Washington, DC, steel expansion joints bubbled along a 21-kilometer stretch of Interstate 66 (Lewis, 1988).

The following sections of this chapter will examine such issues as the portions of the infrastructure that will be significantly affected, and anticipated costs and who will bear them.

PREVIOUS CLIMATE CHANGE STUDIES ON URBAN INFRASTRUCTURE

Available literature on the potential effects of global climate change on urban infrastructure is sparse. Rhoads et al. (1987) examined the potential impacts of sea level rise on water supply and flood protection in Dade and Broward Counties, Florida, and concluded that the effects might be substantial. Linder et al. (1987) estimated that CO_2 doubling might require raising electric capacity by 21% in a southeastern utility and by 10 to 19% in New York State. Hull and Titus (1986) analyzed the potential impact of sea level rise on water supply in the Philadelphia-Wilmington-Trenton area and found that a rise of 0.3 meters could require adding 140 million cubic meters of reservoir capacity, about a 12% increase, to prevent saltwater from advancing past water intakes on the Delaware River. Additional investment would be required to prevent or respond to saltwater infiltration into underground aquifers. Cohen (1987) estimated that large municipalities along the Great Lakes might increase water withdrawals by 5.2 to 5.6% during May to September because of increased lawn watering.

Two recent studies illustrate the importance of considering sea level rise in urban coastal infrastructure planning and the uncertain nature of the decisions involved. Wilcoxen (1986) examined the impact of sea level rise on a portion of San Francisco's sewage transport system buried near the shoreline. The study estimated that if sea level rose 0.6 meters by the year 2100, an expenditure of roughly $70 million on beach nourishment might be required to prevent damage to a structure that cost $100 million to build in the late 1970s. The author suggested that consideration (at no additional cost) of sea level rise in siting the structure could have prevented these expenses. Titus et al. (1987) examined the impact of sea level rise on a proposed coastal drainage system in Charleston, South Carolina, and estimated that a 0.3-meter sea level rise by 2025 would require almost $2.5 million in additional investments to maintain the target level of flood protection. The present value of these investments is

$730,000. In contrast, only about $260,000, one-third of the cost of responding in 2025, would be required to add this level of protection at initial construction. Thus, the investment would be worthwhile if the probability of sea level rising this rapidly exceeds 35%.

URBAN INFRASTRUCTURE STUDY IN THIS REPORT

Several studies undertaken for this report examined some of the implications of climate change in relationship to urban infrastructure. One study comprehensively examined the impacts on infrastructure in several cities:

- Impact of Global Climate Change on Urban Infrastructure - Walker, Miller, Kingsley, and Hyman, The Urban Institute (Volume H)

The following studies, referenced in this chapter, covered issues relating to urban infrastructure:

- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates - Linder and Inglis, ICF Inc. (Volume H)
- Impacts of Extremes in Lake Michigan Levels Along the Illinois Shoreline: Low Levels - Changnon, Leffler, and Shealy, University of Illinois (Volume H)
- Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the Water Supply Systems of the State of California and Atlanta, Georgia -Sheer and Randall, Water Resources Management Inc. (Volume A)
- National Assessment of Beach Nourishment Requirements Associated with Sea Level Rise - Leatherman, University of Maryland (Volume B)
- The Costs of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two-Meter Rise in Mean Sea Level - Weggel, Brown, Escajadillo, Breen, and Doheny, Drexel University (Volume B)
- Effect of Climate Change on Slipping Within Lake Superior and Lake Erie -Keith, DeAvila, and Willis, Engineering Computer Optecnomics (Volume H)

RESULTS OF THE INFRASTRUCTURE STUDY

Impacts on Miami, Cleveland, and New York City

Walker et al. examined three cities distinctly affected by climate change to determine a range of impacts on urban infrastructure.

Study Design

The study was based on a critical review of existing infrastructure studies in the three cities, discussions of likely impacts with local infrastructure experts, analyses undertaken by these experts, and preliminary calculations of probable impacts. Experts were presented with GCM scenarios for CO_2 doubling, and scenarios were used to calculate effects on energy demand, roadways, and other systems. The study also derived conclusions based on experiences in other cities where current temperatures are analogous to temperatures projected for the cities under study, using the analogs identified by Kalkstein (Volume G).

Limitations

The principal limitation of the overall study is the limited use of hydrologic and other modeling. In addition, experts were asked to derive conclusions regarding conditions beyond their experience. Since only three cities are included, the full range of effects on urban infrastructure was not covered. The authors did not perform engineering analyses of cost-effective responses, and they did not assess the potential for reducing impacts through technological change. Thus, these results should be considered as approximations of the costs of impacts and as illustrative of the sensitivity of urban infrastructure to climate change.

Results and Implications

Miami's Infrastructure

Greater Miami is bounded by water on all sides during the rainy season. An extensive network of canals and levees has been built to control ocean and freshwater flooding and to recharge the aquifer beneath the area. Miami has one of the world's most porous aquifers, which lies less than 1.5 meters below the surface in one-third of the developed area. Federal law requires that roughly 15% of Miami's freshwater be released into the Everglades National Park.

The Miami case study examined the probable impacts of climate change and sea level rise on Dade County's water supply, water control and drainage systems, building foundations, roads, bridges, airports, solid waste disposal sites, and sewage transport and treatment systems, assuming that a gradual sea level rise would be managed through strategies such as raising the land in low-lying areas, upgrading levees and dikes with pumped outflows, retreating selectively from some areas, and increasing the freshwater head roughly in proportion to sea level rise to prevent saltwater infiltration into the aquifer.

As Table 13-2 shows, global climate change could require more than $500 million in capital investment in Greater Miami over the next century. Because needed investments in many systems could not be estimated and because a complete engineering analysis was not performed, these results should be considered only as rough estimates. They imply an increase of 1% to 2% in Greater Miami's capital spending for the next 100 years, no more than $20 per household per year at 1985 population levels (Metropolitan Dade County Planning Department, 1988).

Because the south Florida aquifer extends under the ocean, the typical urban response to a rising sea -- diking the water at the surface and pumping out the seepage from ditches behind the dikes -- appears to be unworkable. Unless the dike extended downward more than 45 meters, rising seawater pressure would cause the sea to rush into the aquifer below the surface and push freshwater upward, almost to the surface.

The one-time capital costs for upgrading existing canals and levees in response to a 1-meter sea level rise could be about $60 million. However, almost $50 million in new control structures, including extensive pumping capacity, might be required for the canals used to maintain the freshwater head. Large-scale pumping along canals also could involve substantial operating costs, but these have not been estimated. Storm sewers and drainage would need upgrading, requiring investment of several hundred million dollars above normal replacement costs.

Table 13-2. Probable Infrastructure Needs and Investment in Miami in Response to a Doubling of CO_2 (millions of 1987 dollars)

Infrastructure Need	Cost
Raising canals/levees	60a
Canal control structures	50.00
Pumping	not estimated
Raising streets	250 added to reconstruction cost
Raising yards and houses	not estimated
Pumped sewer connections	note estimated
Raising lots at reconstruction	not estimated
Drainage	200-300
Airport	30.00
Raising bridges	not estimated
Sewer pipe corrosion	not estimated
Water supply	uncertain
Electric generation	20-30% capacity increase

Building foundations generally should remain stable if the freshwater head rises 1 meter because houses are built on concrete slabs, most buildings in newer areas already are built on raised lots to meet Dade County's flood control ordinance, and the foundations of many larger buildings are designed to extend into the water table. Conversely, the water table could infiltrate the base of about a third of Dade County streets, which would have to be raised or risk collapse. If sea level rose gradually, thereby permitting raising of streets and related sewer mains during scheduled reconstruction, the added public cost might be approximately $250 million. Building owners would incur substantial costs to improve drainage, raise yards, raise lots at reconstruction, and pump sewage to mains.

Miami's airport also would need better drainage, requiring an approximately $30 million investment.

A 1-meter rise in sea level would require raising most bridges to ensure adequate clearances and reduce vulnerability to storm surges during hurricanes.

It is unclear what effect climate change will have on hurricanes. Without increased hurricane activity, climate change probably would exacerbate water shortages that are expected to result from population growth in Greater Miami. Thus, climate change could accelerate Miami's long-range plan for large-scale production of desalinated water at three times current water prices. If hurricanes increase, Miami's added expense for water supply might be roughly $100 million to move some wells farther inland. Conversely, increased hurricane frequency and intensity could cause billions of dollars in property damage.

Analysis of Miami's coastal defense and water supply options provides insight into the impacts of sea level rise on cities built on coral reefs, but not into the response of most mainland cities on the U.S. coastline. Dade County is unusual because readily extracted fill is extensively available on public lands having easy access to a canal system that can be navigated by flat-bottomed barges. Nevertheless, this case study suggests that global climate change could cause large coastal cities to invest billions of dollars over the next 50 to 75 years to add and upgrade infrastructure.

Cleveland's Infrastructure

The Cleveland case study examined impacts of climate change on snow and ice control costs, road construction and maintenance, heating and cooling costs and equipment needs, water supply, and storm and wastewater transport. The study also included a preliminary analysis of the effects of a drop in the level of Lake Erie as estimated by Croley (see Chapter 15: Great Lakes). The impact on the snow and ice control budget was estimated by analogy to the budget in Nashville, Tennessee.

Results are displayed in Table 13-3, which shows that the net impact of climate change on Cleveland's annual infrastructure costs could be negligible, although expenditures probably would shift between categories. In addition to the costs shown in Table 13-3, a one-time capital expenditure of $68 to $80 million could be required to add air conditioners in public buildings. Also, many private residences probably would install air conditioners.

Walker et al. estimated that global climate change could cause annual snowfall in Cleveland to drop from 1.25 to roughly 0.2 meters (4.1 to 0.7 feet), reducing annual snow and ice control costs by about $4.5 million. Decreased frost damage to roads and bridges could yield further savings estimated at $700,000 per year. A drop of $2.3 million per year in heating costs for public buildings also was estimated. Conversely, annual public air-conditioning costs seemed likely to rise by $6.6 to $9.3 million. The impacts on the transit operating budget seemed likely to mirror the impacts on the general budget, with reduced mishaps and traffic delays in ice and snow offsetting increased fuel costs for vehicle cooling.

Table 13-3. Estimated Impacts of a CO_2 Doubling on Cleveland's Annual Infrastructure Costs (millions of 1987 dollars)

Infrastructure category	Annual operating costs
Heating	-2.3
Air-conditioning	+6.6-9.3
Snow and ice control	-4.5
Frost damage to 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
Storm water system	negligible
Total	-1.6 to +$1.1

Source: Walker et al. (Volume H); Keith et al. (Volume H).

The study suggested Cleveland might spend about \$65 to \$80 million to add air-conditioning to older schools and to large nonoffice spaces such as gyms and repair garages. Much of this expenditure would occur as buildings were replaced or refurbished and might have occurred even without climate change.

The rise in winter temperatures associated with a doubling of CO_2 might allow Cleveland to use thinner pavement, resulting in possible savings of about 3% in road resurfacing costs and 1% in reconstruction costs. The net savings could average about \$200,000 per year or 1.3% of the city's current capital budget. Engineering standards (AASHTO, 1987) suggested that the rate of pavement deterioration probably also should decline as winter temperatures rise, saving roughly \$500,000 per year.

A climate-induced drop in the level of Lake Erie probably would not adversely affect Cleveland, although some dredging might be required in the Cuyahoga River and port area (Keith et al., Volume H). Upgrading of the city's combined storm and wastewater collection system appeared to be unnecessary, although this would depend upon rainfall variability.

If temperature rises several degrees, most northern cities probably could anticipate savings in snow and ice control, heating, and roadway construction and maintenance costs similar to those described for Cleveland. These savings might approximately offset the increase in air-conditioning costs. More southern cities could experience modest budget increases.

Cleveland could become a more attractive location for water-intensive industry if water supplies in other areas become less reliable. Resulting in-migration could bring further growthrelated infrastructure costs. Lower Great Lakes levels could require dredging, modification to ports, and relocation of some water intakes. (For a further discussion of these issues, see Chapter 15: Great Lakes.)

New York City's Water Supply

New York City's infrastructure may be affected in many ways by global climate change. Temperature change could affect the same capital expense categories in both New York City and Cleveland. In addition, the city may have to gradually raise its dikes and better protect underground infrastructure from seawater infiltration. Interpolating from Weggel et al. (Volume B), approximately \$120 million might be invested to protect shorelines from a sea level rise of 1 meter. The most pressing, and perhaps largest, problem facing the city may be the effects of global climate change on the adequacy of the city's water supply. The New York City study focused on that issue. Table 13-4 provides estimates drawn from a number of studies about possible infrastructure impacts on New York City.

The New York metropolitan area draws water from the adjoining Hudson and Delaware River Basins and from underground aquifers serving coastal New Jersey and Long Island. Figure 13-1 shows the region and its water supply sources.

Table 13-4. Probable Impacts of a CO_2 Doubling on Selected Infrastructure m the New York Metropolitan Area (millions of 1987 dollars)

Infrastructure category	Costs
Upgrading levees	120
Drainage	increased flooding in low-lying area, minimal sewer system changes
Sewer outflows	more frequent inspection
Water supply	3,000
Snow and ice control	reduced substantially
Road maintenance and construction	winter savings, offset by melting asphalt in Manhattan
Mass transit	summer increase offsets winter savings
Electricity production	65-150
Heating	reduced

Note: Impacts on underground infrastructure, airports, and ports have not been probed, but a discussion of these impacts among Port Authority representatives and other experts at the Second North American Conference on Preparing for Climate Change, Washington, DC, December 7, 1988, suggested they would be small.

Source: Walker et al. (Volume H): Weggel et al. (Volume B); Linder et al. (1987); Schwarz and Dillard (1989).

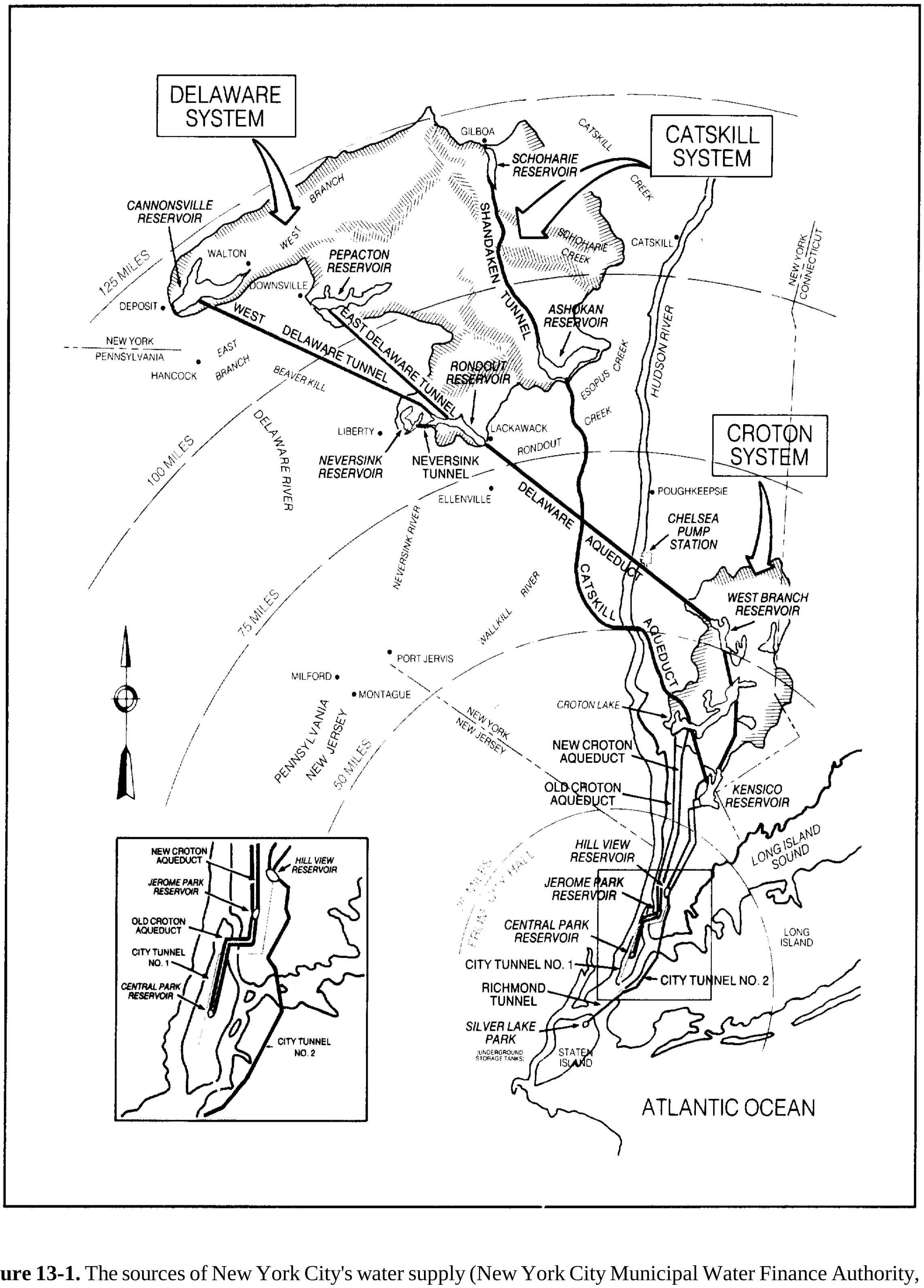

Figure 13-1. The sources of New York City's water supply (New York City Municipal Water Finance Authority, 1986).

The water supply network is in deficit. The Mayor's Task Force (1987) has recommended remedying New York City's portion of the deficit through better management of water demand and detailed study of the possibility of reactivation of a water intake at Chelsea, a $223 to $391 million investment that would yield 375 to 750 million liters of water daily.

Walker et al. estimated changes in water demand using design standards for commercial cooling-tower demand, changes in electricity demand estimated by Linder et al. (1987), and historic residential summer water use. The impact of sea level rise on water supply was estimated by analogy using Hull and Titus (1986), which analyzes possible saltwater advance up the Delaware River. The impact on reservoir supply also was estimated by analogy, using a Great Lakes water balance model (Linder et al., 1987). Walker et al. assumed that baseline demand would not increase above projected demand in 2030, potentially underestimating the increased demand for water.

Walker et al. estimated that a rise in temperatures consistent with the GISS and GFDL scenarios would mean about a 20% increase in cooling degree days. In response, average daily demand for water used in cooling large buildings could increase by 190 million liters during the summer, and increased lawn watering could raise demand by 110 million liters per day, thereby generating a 5% rise in annual demand.

Higher temperatures could increase evaporation and evapotranspiration, decreasing the ability to store water efficiently in surface impoundments. The water balance model indicated the supply loss could range from 10 to 24%.

Saltwater infiltration due to rising sea level would further reduce supply. The study suggested that a 1-meter sea level rise could place the proposed $300 million Chelsea intake below the salt line during the peak summer demand period in mild drought years, reducing supply another 13%. Larger sea level rise or greater droughts might prevent use of the existing Poughkeepsie intake during severe droughts, further reducing supply. In addition, subsurface infiltration could reduce the supply available from the Long Island aquifer.

In summary, a doubled CO_2 atmosphere could produce a shortfall equal to 28 to 42% of planned supply in the Hudson River Basin.

Implications Arising from Other EPA Studies in This Report

Linder and Inglis (Volume H; Chapter 10: Electricity Demand) suggest that increased air conditioning use could raise peak electricity demand by 10 to 30% in the southern half of the United States. Nationally, utilities supplying the northernmost cities could experience decreased demand, while those supplying cities in the remainder of the country could experience electricity needs higher than they have anticipated. Sheer's study of California (see Chapter 14) water supply suggests that new surface water impoundments may be needed to meet urban water needs and other demands. The coastal defense strategies suggested in Chapter 7: Sea Level Rise would apply to most urban coastal areas, especially those along the Atlantic and Gulf coasts.

Changnon et al. (Volume H) conclude that a falling lake level might prompt investment of $200 to $400 million to adapt recreational and commercial harbors and beach facilities, and an investment of $20 million to adjust water supply intakes and sewer outfalls along the Illinois shoreline of Lake Michigan, with similar costs likely on the other Great Lakes. The Keith study (see Chapter 15: Great Lakes) suggests that each commercial harbor on Great Lakes Erie and Superior could spend $5 to $30 million on dredging to maintain harbor access.

RESULTS OF RELATED STUDIES

Metropolitan Water Supply

Schwarz and Dillard (1989) conducted telephone interviews with local infrastructure managers to identify the probable impacts of global climate change on water supply and drainage in several metropolitan areas. Results from some cities are discussed here.

Washington, DC

Longer hot spells could warm the Potomac River and cause trihalomethane formed during chlorination to rise above allowable limits. Remedying this could require a capital investment of roughly $50 to $70 million and could increase treatment costs. Also, lawn watering probably would increase during long spells of hot, dry weather. Although a substantial decrease in runoff could reduce supply in parts of the system, the availability of additional storage capacity would make a shortage unlikely.

New Orleans

Sea level rise could necessitate moving the water intakes considerably farther up the Mississippi and replacing cast iron water mains that would corrode if exposed to saltwater. Reduced riverflow also could increase settling and treatment requirements. Rising sea level could increase saltwater infiltration into the water system and could require increased pumping capacity.

New York City

This study raised many of the same concerns regarding water supply and demand as the study by Walker et al. (Volume H) and indicated that even a 0.25-meter sea level rise would mean the proposed Chelsea intake was too far downstream. The sanitary and storm sewage system capacity and design probably would not need revision. Nevertheless, in a few low-lying areas, higher sea level could increase sewer backups, ponding, and basement flooding when high tides coincided with high runoffs.

Tucson

Tucson is depleting its aquifer despite substantial conservation efforts and lawn watering with treated wastewater. Higher temperatures would increase demand and tighten supply, possibly jeopardizing the city's ability to draw on water from the Central Arizona Project on the already strained Colorado River. While modest savings might be achieved through stricter conservation measures and more wastewater use, purchase of water in the regional market most likely would be the only practical response to climate-related shortfalls.

IMPLICATIONS FOR URBAN INFRASTRUCTURE

The implications of climate change for urban America vary spatially. Some localities, especially those along the Great Lakes, might experience roughly offsetting gains and losses. Others especially those along the coastlines and in watershort areas, could bear increased infrastructure costs. The costs would be especially high if changes came through abrupt "sawtooth" shifts or increases in extreme events, making it difficult to adapt infrastructure primarily during normal repair and replacement. The likely impacts of an effective doubling of atmospheric CO_2 could affect a wide range of infrastructure. Additional climate change effects beyond doubled CO_2 or sea level rise above 1 meter could result in even greater costs.

Water

Hotter temperatures could cause faster evaporation of groundwater and raise the demand for water to support commercial air- conditioning systems and lawn watering. Earlier snowmelt in the West could force a lowering of dam levels to ensure availability of enough capacity to control flood waters. At the same time, sea level rise could cause saltwater to advance up rivers and to infiltrate into coastal aquifers. In droughts, many existing water intakes might deliver brackish water.

The solution to these problems could involve strong conservation measures, such as miles of aqueducts from new water intakes at higher river elevations, new reservoirs, sewage effluent recycling systems to support commercial cooling or lawn watering, and perhaps desalinization efforts along the coasts. The solution for the New YorkPhiladelphia corridor alone is likely to cost $3 to $7 billion. Communities in the Delaware River Basin, northern New Jersey, the lower Hudson, and Long Island might well form a multistate water supply and management district of unprecedented size and complexity to handle financing and capital construction.

Drainage and Wastewater Systems

Increased storm size and intensity could tax many storm sewer systems. Sea level rise also could reduce coastal flood protection levels in low-lying areas. The resulting increases in flooding and releases of untreated waste into watercourses from combined storm and wastewater systems probably would motivate new sewer investments. In Dade County alone, costs to maintain flood protection at existing levels could be $200 to $300 million if sea level rose 1 meter.

Temperature rise could increase hydrogen sulfide formation in sewer pipes, leading to internal corrosion and eventual failure. In coastal areas with increased ocean flooding, storm sewers would carry corrosive saltwater with increased frequency. Sea level rise also could cause more pipes in coastal areas to face the external risk of corrosive seawater. More frequent inspection and earlier replacement of much existing pipe, as well as a gradual shift to more corrosion-resistant pipe with plastic lining, might be required.

Coastal Defenses

Protection from a rising sea could require periodic investment in many major coastal communities. In urban areas, a common approach might be the New Orleans solution, where extensively developed coastal areas are protected by dikes, and covered drainage ditches behind the dikes are pumped to keep out the saltwater.

Roads

Rising temperatures could reduce the costs of road construction and maintenance. Snow and ice control costs might drop dramatically. A decrease in deep freezes and freeze-thaw cycles also would mean fewer potholes. Warmer temperatures and the improved drainage resulting from higher evaporation rates could permit use of thinner pavements in many areas, but could require enhanced expansion capabilities.

Bridges

Sea level rise and increased storm intensity could require upgrading of many bridges either through costly retrofit or as part of normal reconstruction. The range of temperature accommodated by expansion joints also might need to be increased. The costs might be modest if bridge planners upgraded in anticipation of climate change.

Mass Transit

In the North, buses and railcars could experience fewer snow-related delays. Conversely, slight increases in fuel costs could result from increased use of air conditioners.

Electricity and Air-Conditioning

Hotter temperatures could increase air-conditioning use. Consequently, peak load capacity to generate electric power might have to increase in response to global climate change. Fortunately, airconditioning equipment is replaced frequently, so increased loads on existing equipment could be accommodated incrementally. Some houses and public buildings in northern climates might need to add air-conditioning, but such retrofitting has been performed since the first window air conditioners were introduced.

POLICY IMPLICATIONS

The possibility of global climate change increases the risks of infrastructure investment. Application of design standards and extrapolation from historical data still may not provide reasonable assurance that water and power supply, dam strength and capacity, bridge clearances, or storm sewerage capacity will be adequate for the 35-, 50-, and 100-year design cycles of these facilities. For example, the National Flood Insurance Program's maps identifying the historical 100-year floodplain and 500-year floodway may no longer provide a reliable basis for local building and zoning ordinances designed to minimize flood losses to life and property.

Investment Analysis Methods

Especially in coastal areas, the possibility of global climate change may soon require careful decisions regarding how and when to adapt the infrastructure. A strong emphasis on lifecycle costing and upgrading during reconstruction in anticipation of future changes could yield large, long-term cost savings. To accomplish this goal, such institutions as the Department of Housing and Urban Development might work with the American Public Works Association, the National League of Cities, the U.S. Conference of Mayors, the American Planning Association, and similar groups to educate their constituencies regarding the uncertainties and ways to incorporate them into the decisionmaking process.

Water Supply

Water supply is of particular concern because decades are required to plan and complete projects, which then might last 100 years. Dams, reservoirs, and water intakes currently being planned and built could become obsolete or inadequate as a result of global climate change. Elsewhere, communities might be allowing development of land needed for reservoirs to meet the water shortages that would result from climate change.

Such federal agencies as the U.S. Geological Survey, U.S. Army Corps of Engineers, and EPA may wish to work with states and municipalities to study the possible impacts of climate change on the water supply of major metropolitan areas.

Water supply investments frequently affect multistate areas, creating a need for federal coordination. The Supreme Court has been forced to settle previous water rights disputes concerning many major rivers, and global climate change might well generate new disputes. Cost-effective response to climate change also might require new multistate water projects. For example, a major project on the Hudson River that allowed New York City to reduce its use of Delaware River water might be the least costly way to increase water supply in Philadelphia. The upcoming state debates over water supply financing should be informed by the lesson of past infrastructure crises: water piping and pumping costs resulting from global climate change should be fully recovered from the water users to avoid stimulating artificial demand for bargain water.

Infrastructure Standards

Voluntary standards organizations, such as the American Society of Civil Engineers, the Building Officials and Code Administrators International, and the American Association of State Highway and Transportation Officials, may wish to educate their committees on global climate change. Growing uncertainty concerning future temperature, precipitation, and sea levels might dictate a reassessment of existing standards and safety factors for ventilation, drainage, flood protection, facility siting, thermal tolerances, resistance to corrosion, and so forth. Conversely, prompt detection of lasting changes could allow adjustment of geographically based standards -- for example, on roadbed depth and home insulation levels -- and provide significant savings. Thus, the standardmaking organizations might beneficially establish policies concerning how and when their committees should account for global climate change or educate their committees about the prospects.

RESEARCH NEEDS

The following are recommended for further research:

1. More case studies of urban impacts, with priority on a west coast city and an inland city. Issues of particular interest include the effects on subsidence problems in cities similar to Phoenix, the implications for sewage treatment capacity in areas where more frequent and intense periods of low riverflow could reduce acceptable effluent discharge rates, the impact on bridge replacement costs, and the potential for and probable consequences of saltwater infiltration into pipes in older coastal communities.

2. The probable impacts of global climate change on domestic and international migration flows and the infrastructure demands these flows produce. Heat and high water prices might drive jobs and people away from some regions, while others might flourish. Infrastructure investment in new water supply, for example, might be unnecessary in areas that would lose population, but extra capacity might be needed in areas where population would grow. Similarly, as climate change shifts the best growing areas for specific crops, new farm-to-market transportation networks might need to be developed. Rights-of-way for these systems might best be set aside now, before land prices rise in response to climate change.

REFERENCES

AASHTO. 1987. American Association of State Highway and Transportation Officials. Manual for the Design of Permanent Structures, Appendix A. Treatment of Roadbed Swelling and/or Frost Heave Urban Infrastructure in Design. Washington, DC: American Association of State Highway and Transportation Officials.

Bruske, E. 1988. 104 (phew') degrees hottest in 52 years. The Washington Post 111(225):Al, A6. July 17.

Cohen, S.J. 1987. Projected increases in municipal water use in the Great Lakes due to CO_2 induced climatic change. Water Resources Bulletin 23(1):91-101.

Hirsch, J. 1988. As streets melt, cars are flummoxed by hummocks. The New York Times 137(47599):B1, B5. August 16.

Hull, C.H.J., and J.G. Titus, ed. 1986. Greenhouse Effect, Sea Level Rise, and Salinity in the Delaware Estuary. Washington, DC: U.S. Environmental Protection Agency. Publication No. 230-05-86-010.

Lewis, N. 1988. Two more heat records fall as summer of 1988 boils on. The Washington Post 111 (257):Al, A10, All. August 18.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. ICF Incorporated. 1987. Potential Impacts of Global Climate Change on Electric Utilities. Albany, NY: New York State Energy Research and Development Authority. Publication No. 824-CON-AEP-86.

Mayor's Intergovernmental Task Force on New York City Water Supply Needs. 1987. Managing for the Present, Planning for the Future; December.

Metropolitan Dade County Planning Department. 1988. Comprehensive Development Master Plan for Metropolitan Dade County, Florida. July 1979, July 1985, June 1987, and April 1988.

National Council on Public Works Improvement. 1988. Fragile Foundations - Final Report to the President and Congress, Washington, DC; February.

New York City Municipal Water Finance Authority. 1986. Water and Sewer System Revenue Bonds, Fiscal 1986, Series A. Prospectus. New York.

Rhoads, P.B., G.C. Shih, and R.L. Hamrick. 1987. Water resource planning concerns and changing climate: a Florida perspective. In: Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues. Norman, OK: University of Oklahoma, pp. 348-363.

Schwarz, H.E., and L. Dillard. 1989. Urban water. Chapter III-D. In: Waggoner, P.E., ed. Climatic Variability, Climate Change, and U.S. Water Resources. New York: John Wiley and Sons. In press.

Sossaman, B.A. 1988a. News release. U.S. Army Corps of Engineers, New Orleans District. June 28.

Sossaman, BA. 1988b. News release. U.S. Army Corps of Engineers, New Orleans District. July 15.

Statistical Abstract of the United States. 1988. Washington, DC: U.S. Government Printing Office.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Webb, and J.O. Waddell. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. Journal of Water Resources Planning and Management 113(2):216-227.

The Washington Post. 1988. Warped rails checked in Amtrak wreck. 111(246):A5. August 7.

Wilcoxen, P.J. 1986. Coastal erosion and sea level rise: implications for Ocean Beach and San Francisco's Westside Transport Project. Coastal Zone Management Journal 14(3):173-191.

CHAPTER 14
CALIFORNIA

FINDINGS

Global warming could cause higher winter runoff and lower spring runoff in California and increase the difficulty of meeting water supply needs. It could also increase salinity in the San Francisco Bay and the Sacramento-San Joaquin Delta and increase the relative abundance of marine species in the bay; degrade water quality in subalpine lakes; raise ambient ozone levels; increase electricity demand; and raise the demand for water for irrigation.

Water Resources

- Higher temperatures would lead to higher winter runoff from the mountains surrounding the Central Valley, because less precipitation would fall as snow, and the snowpack would melt earlier. Runoff in the late spring and summer consequently would be reduced.

- As a result, the amount and reliability of the water supply from reservoirs in the Central Valley Basin would decrease. Annual water deliveries from the State Water Project (SWP) could be reduced by 200,000 to 400,000 acre-feet or 7 to 16%. In comparison, the statewide increase for water from the SWP, due to nonclimate factors such as population growth, may total 1.4 million acre-feet by 2010. Even if operating rules were changed, current reservoirs would not have the capacity to store the heavier winter runoff and at the same time retain flood control capabilities.

- Rising sea level could increase the possibility of levee failure. If the delta and bay levees failed and sea level rose 1 meter (40 inches) by 2100, agriculture in the delta region would be almost eliminated, the pumping of freshwater out of the delta to users to the south could be jeopardized by increasing salinity, and the area and volume of the estuary could triple and double, respectively. Even if the levees were maintained, the estuary could still increase in area and volume by 30 and 15%, respectively, as a result of a 1-meter sea level rise alone.

- Sea level rise of 1 meter could cause saline (brackish) water to migrate inland between 4 and 10 kilometers (2.5 and 6 miles, respectively) if the levees fail and if tidal channels do not erode. Freshwater releases into the delta might have to be doubled to repel saline water near the major freshwater pumping facilities.

Wetlands and Fisheries

- The wetlands in the San Francisco Bay estuary would be gradually inundated as sea level rises faster than the wetlands accrete sediments. The amount of wetlands lost would be a function of the rate of sea level rise and of whether shorelines are protected. If sea level rises 1 meter by 2100, the rate of rise will be greater than wetland vertical accretion by the middle of the next century. If sea level rises 2 to 3 meters by 2100, wetland inundation will begin early in the 21st century.

- If salinity increases within the San Francisco Bay estuary, wetland vegetation will shift from brackish and freshwater species to more salt tolerant plants. This shift could severely reduce waterfowl populations that depend on freshwater habitats. The timing, magnitude, and location of phytoplankton production could shift. Marine fish species could increase in abundance, while saltwater species that breed in freshwater areas would most likely decline.

- Higher temperatures in subalpine lakes could increase annual primary production (such as algae) by between 16 and 87%, which could degrade lake water quality and change the composition of fish species.

Agriculture

- The impacts of climate change on agriculture in California are uncertain. The effects of changes in temperature and precipitation alone would most likely reduce yields by 3 to 40%, depending on the crop. However, with the combined effects of climate and higher CO_2 levels, yields for all modeled crops, except corn and sugarbeets, might increase.

- The potential growth in irrigation in some parts of the state may require increased extraction of groundwater because of current full use of surface water supplies. This would decrease water quality and affect water management options.

- Yields in California may be less adversely affected than those in most parts of the country. Crop acreage could increase because of the shifts in yields and the presence of irrigation infrastructure.

Natural Vegetation

- Drier climate conditions could reduce forest density, particularly pine and fir trees, and timber productivity. (The full impacts on California forests were not assessed in this report.)

Air Quality

- If today's emissions exist in a future warmer climate, ozone levels in central California could increase and could change location because of higher temperatures. As a result, the area in central California with ozone levels exceeding EPA standards (0.12 parts per hundred million (pphm)) on a given day could almost double unless additional steps are taken to control emissions. These additional controls would increase the cost of pollution control.

Electricity Demand

- The annual demand for electricity in California could rise by 3 to 6 billion kilowatthours (kWh) (1 to 2%) over baseline demand in 2010 and by 21 to 41 billion kWh (3 to 5%) over baseline demand in 2055.

- By 2010, 2 to 3 gigawatts (GW) would be needed to meet the increased demand. By 2055, 10 to 20 GW would be needed -- a 14 to 20% increase over baseline additions that may occur without climate change. The additional capital cost by 2055 would be $10 to $27 billion (in 1986 dollars).

Policy Implications

- Water management institutions, such as the U.S. Bureau of Reclamation and the California Department of Water Resources, should analyze the potential impacts of climate change on water management in California. They should consider whether and how the Central Valley Project and State Water Project should be modified to meet increasing demands in the face of diminishing supplies due to climate change. They may also consider whether to change water allocation procedures to encourage more efficient use of water.

- The California Water Resources Control Board should consider the impact of climate change on surface and groundwater quality.

- State and local entities should consider the impacts of climate change on levee and wetland management in San Francisco Bay and the delta.

- The California Air Quality Board should review the long-term implications of climate change on air quality management strategies.

- The California Energy Commission should consider the impacts of climate change on the energy supply needs for the state.

CLIMATE-SENSITIVE RESOURCES OF CALIFORNIA

California's Central Valley is the most productive and diverse agricultural region of its size in the world. The Central Valley Basin, which includes the drainages of the Sacramento and San Joaquin Rivers, encompasses several large metropolitan areas, dispersed manufacturing, major port facilities, important timber reserves, heavily used recreational areas, and diverse ecosystems.

Much of the region's economic and social importance is derived from its water resources. Over 40% of California's total surface water runoff drains from the Central Valley Basin into the San Francisco Bay area (Miller and Hyslop, 1983). The basin supplies water for irrigated agricultural, municipal, and industrial uses, and for a host of other resources and activities.

The Central Valley Basin encompasses approximately 40% of California's land area (Figure 14-1). Elevations range from just below sea level on leveed islands in the Sacramento-San Joaquin River Delta to peaks of over 4,200 meters (14,000 feet) in the Sierra Nevada (Figures 14-2 and 14-3). Mountains ring most of the basin: the Sierra Nevada along the eastern side and the Coast Ranges on the west. The only outlet to the Pacific Ocean is via the San Francisco Bay estuary (Figure 14-2).

Current Climate

California's climate is characterized by little, if any, summer precipitation and by generally wet winters (Major, 1977). Both temperature and precipitation vary with elevation and latitude in the Central Valley Basin. Extremes in mean annual precipitation range from about 15 centimeters (6 inches) in the southern San Joaquin River Basin to about 190 centimeters (75 inches) in the mountains of the Sacramento River Basin. While almost all valley floor precipitation falls as rain, winter precipitation in the high mountains often falls as snow. Storage of water in the snowpack controls the seasonal timing of runoff in the Central Valley rivers and has shaped the evolution of strategies for water management and flood protection. Under current climatic conditions, peak runoff occurs between February and May for individual rivers within the Central Valley Basin (California Department of Water Resources, 1983; Gleick, 1987b).

Water Resources

Water Distribution

California's water resources are poorly distributed relative to human settlement patterns in the state. Over two-thirds of the state's surface water supply originates north of Sacramento, and 70% of its population and 80% of its total demand for water lie to the south (California Department of Water Resources, 1985). In addition, about 85% of the Central Valley Basin's total annual precipitation occurs between November and April, whereas peak water use occurs during the summer.

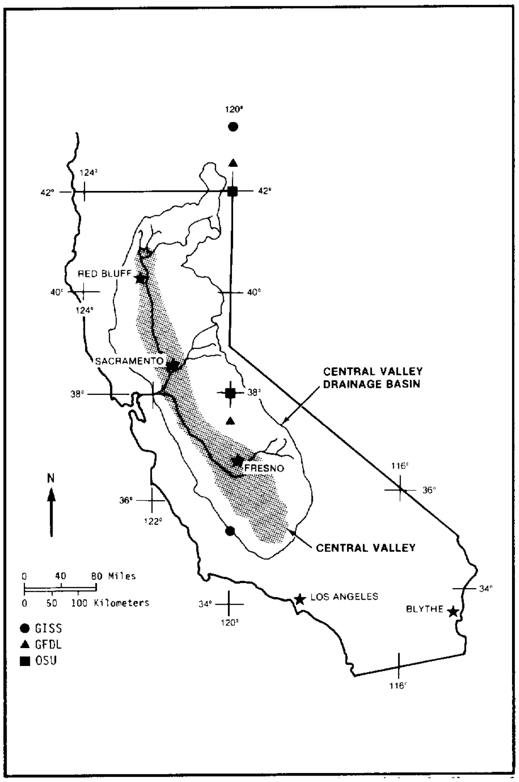

Figure 14-1. The Central Valley (shaded) and Central Valley Drainage Basin of California. Symbols refer to locations of general circulation model (GCM) gridpoints. (See California Regional Climate Scenarios section of this chapter for details on GCMs).

In working to solve these water distribution problems, the U.S. Government and California have built two of the largest and most elaborate water development projects in the world: the Federal Central Valley Project (CVP) and the California State Water Project (SWP). Both are essentially designed to move water from water-rich northern California to the water-poor south, and to supply water for agricultural, municipal, and industrial purposes. Currently, the CVP has a water surplus and the SWP has a shortage, especially in relationship to users' projected requirements. Thus, the SWP is particularly susceptible to dry years.

<u>Flood Control and Hydroelectric Power</u>

Another objective of the CVP and SWP is flood control. By 1984, CVP facilities had prevented almost $500 million in flood damages (U.S. Bureau of Reclamation, 1985). Flood control, however, comes at the expense of water storage (and hence water deliveries), because reservoir levels must be kept low to absorb high riverflows during the rainy season.

Hydroelectric power generation is also an objective of the CVP and SWP, and surplus power is sold to utility companies. CVP powerplants produce an average of 5.5 to 6 billion kWh per year. In 1976 and 1977, precipitation was 35 and 55% below normal, respectively, and hydroelectric power generation fell to 50 and 40%, respectively, of target production.

<u>Sacramento-San Joaquin River Delta</u>

The delta at the confluence of the Sacramento and San Joaquin Rivers is the focal point of major water-related issues in California (Figure 14-3). For example, most islands in the delta lie below sea level and are protected by levees, some of which are made of peat and are relatively fragile. These islands would be vulnerable to inundation from rising sea level associated with climate warming. The deep peat soils on these islands support highly productive agriculture that would be lost if inundated.

In addition to agricultural importance, the delta is also the source of all CVP and SWP water exports to points farther south, and in this regard basically functions as a transfer point of water from the north to the south. The freshwater pumping plants (see Figure 14-3) in the delta are the largest freshwater diversions in California (Sudman, 1987). Delta outflow must be maintained at a required level to prevent saltwater intrusion into the pumping plants. The volume of water released from upstream reservoirs to achieve this level is known as carriage water.

<u>Commerce</u>

The San Francisco Bay estuary includes the largest bay on the California coast (see Figure 142). The bay's northern reach between the Golden Gate and the Sacramento-San Joaquin River Delta is a brackish estuary dominated by seasonally varying river inflow (Conomos et al., 1985). The southern reach between the Golden Gate and the southern terminus of the bay is a tidally oscillating lagoon-type estuary. The port facilities of the San Francisco Bay area are vital to California's internal trade, to Pacific coast commerce, and to foreign trade, particularly with Asian countries. The ports of Oakland and San Francisco, combined, ranked fourth in the United States in tonnage of containerized cargo handled in 1983 (U.S. Maritime Administration, 1985). These facilities and operations are sensitive, in varying degrees, to both sea level change and fluctuation in freshwater runoff.

Agriculture

California annually produces about 10% of the cash farm receipts in the United States and produced $14.5 billion in farm income in 1986 (U.S. Department of Agriculture, 1987). Central Valley farms make up significant proportions of total U.S. production of many crops, including cotton, apricots, grapes, almonds, tomatoes, and lettuce.

Agriculture, the primary land use and the largest consumer of water in the Central Valley Basin, accounts for 87% of total net water use in the region. Furthermore, the region accounts for 72% of total net water use for the entire state and almost 80% of net agricultural use (California Department of Water Resources, 1987a).

Forestry

Silviculture is extensively practiced in California's mountains. The nine national forests substantially within the Central Valley Basin recorded over $88.6 million in timber sales in fiscal year 1986 (U.S.

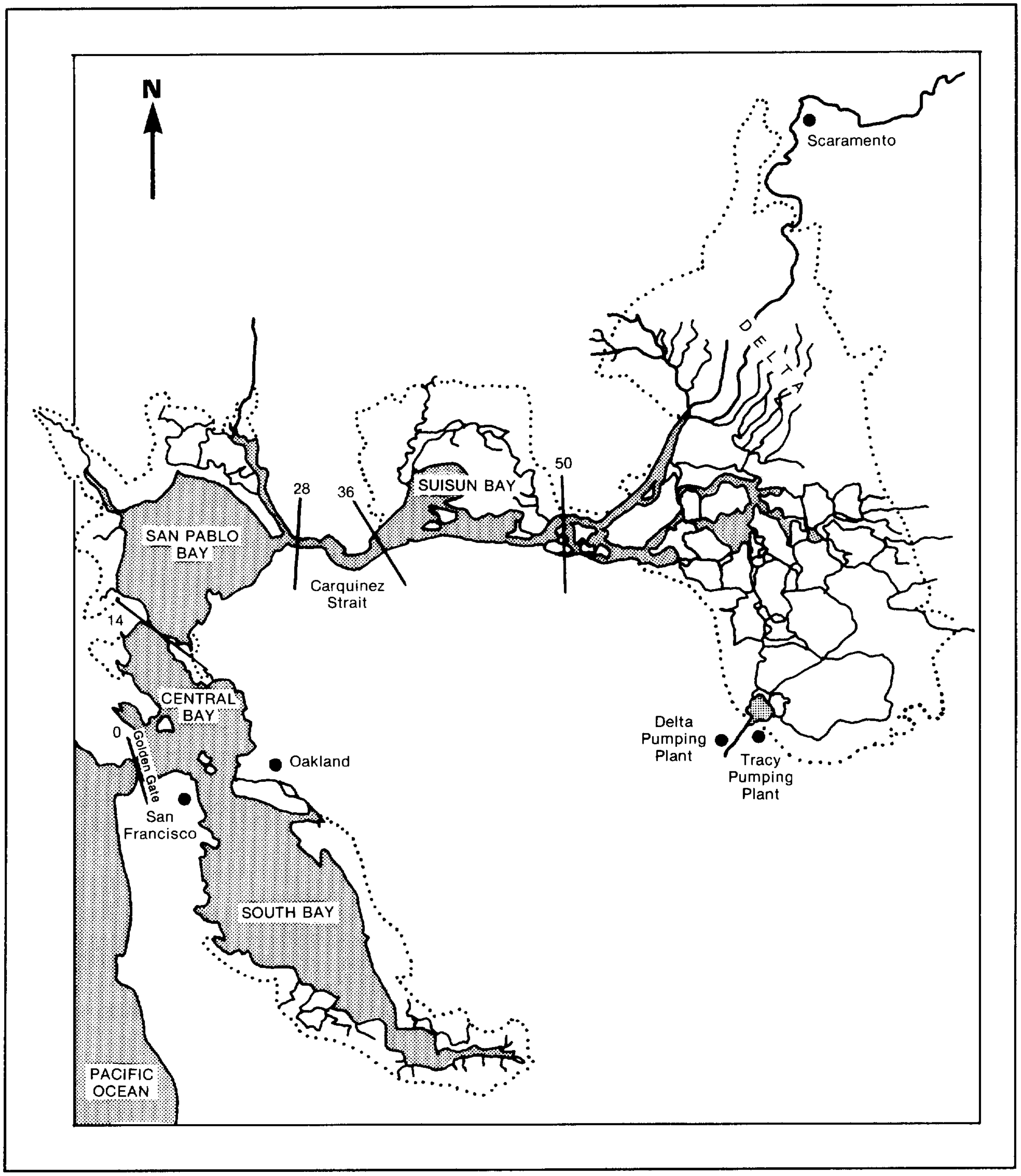

Figure 14-2. The San Francisco Bay estuary and locations of the freshwater pumping plants in the delta. The numbered bars indicate distance (in miles) from the Golden Gate. The dotted line indicates the maximum area affected by a 100-year high tide with a 1-meter (40-inch) sea level rise.

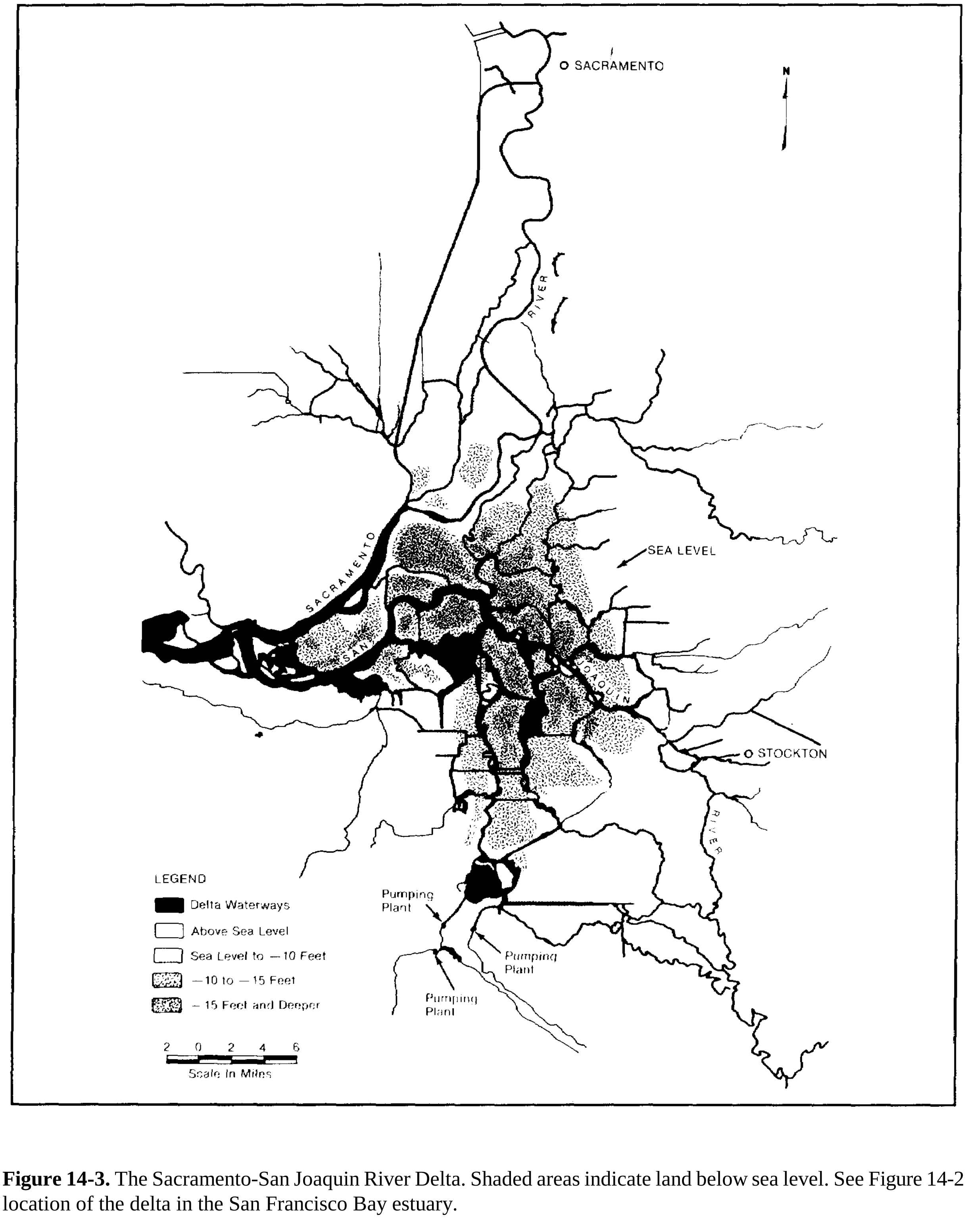

Figure 14-3. The Sacramento-San Joaquin River Delta. Shaded areas indicate land below sea level. See Figure 14-2 for location of the delta in the San Francisco Bay estuary.

Department of the Interior, 1986). Forest productivity is sensitive to climate variation. For example, the drought of 1976-77 contributed to significant tree mortality because of large infestations of bark beetles (California Division of Forestry and Fire Protection, 1988).

Natural Vegetation

Approximately one-fourth of all the threatened and endangered plants in the United States are found in California. About 460 species, or about 9% of the California species listed by Munz and Keck (1959), are either extinct or in danger of becoming extinct.

California contains about 5,060 native vascular plant species; of these, about 30% occur only in California (Munz and Keck, 1959; Raven, 1977). These species are more numerous than those present in the entire central and northeastern United States and adjacent Canada, a region about eight times larger than California (Fernald, 1950).

Within the Central Valley Basin, terrestrial vegetation may be grouped into the following broad classes, listed according to decreasing elevation: alpine, subalpine forest, montane forest, mixed evergreen forest, chaparral and oak woodland, and valley grassland (Barbour and Major, 1977).

Wetlands

The San Francisco Bay estuary includes approximately 90% of the salt marsh area in California (Macdonald, 1977). Nichols and Wright (1971) documented a 60% reduction in San Francisco Bay marsh between 1850 and 1968. This reduction was largely the result of reclamation for salt ponds, agriculture, expanding urbanization, shipping facilities, and marinas. Further loss of wetlands could result in substantial ecological and economic losses for the region. For example, the managed wetlands north of Suisun Bay support a hunting and fishing industry producing over $150 million annually (Meyer, 1987). Tourism, rare and endangered species, and heritage values also could be harmed.

Wildlife and Fisheries

The San Francisco Bay estuary provides vital habitat for many bird and fish species (California Department of Water Resources, 1983). The estuary is an important wintering area for waterfowl of the Pacific flyway. Important sport fish include striped bass, chinook salmon, sturgeon, American shad, and steelhead rainbow trout. These species are anadromous (i.e., saltwater species that enter freshwater areas for breeding), and the delta is an important nursery for these species. Chinook salmon also constitute an important commercial fish species, and Central Valley rivers support about 75% of California's chinook salmon catch, valued at $13.4 million at 1981 prices. The populations of these species are affected by water quality in the estuary.

To protect aquatic organisms in the delta, the State Water Resources Control Board (SWRCB) adopted water right Decision 1485 in 1978 that sets water quality standards to protect the delta and Suisun Marsh. The standards vary from year to year, with less stringent requirements in dry years. The standards are achieved by meeting minimum delta outflow requirements. If delta outflow falls below the required level, then releases from upstream state and federal reservoirs must be increased so that the outflow requirement is met. The water quality standards take precedence over water export from the delta.

Recreation and Nature Preservation

Recreation and nature preservation are important in California. Major recreational areas in the Central Valley Basin include four national parks (Lassen Volcanic, Sequoia, Kings Canyon, and Yosemite) and nine national forests that lie either completely or largely within its boundaries. Two national recreation areas and 13 designated wildlife refuges and management areas also are situated in the region. Downhill skiing and other winter sports are economically important in the state. Water projects throughout the Central Valley Basin provide significant recreational opportunities.

PREVIOUS CLIMATE CHANGE STUDIES

Two of the few studies previously undertaken to assess the potential effects of climate change on the region are discussed in this section.

Forests

Leverenz and Lev (1987) estimated the potential range changes, caused by CO_2-induced climate change, for six major commercial tree species in the western United States. Two of the species, ponderosa pine and Douglas-fir, have significant populations in California. Leverenz and Lev based their estimates of range changes on the species' response to increased temperature, decreased water balance, and higher CO_2 concentrations. The scenario of climate change used was based on a simulation using the Geophysical Fluid Dynamics Laboratory (GFDL) model (a different run from that used for this study), with CO concentrations double their present levels. heir results suggest that in California, ponderosa pine could increase in range and abundance because of its ability to withstand long summer drought. Douglas- fir could be eliminated from coastal lowlands in California but might occur in coastal areas at higher elevations.

Water Resources

Gleick (1987a,b) applied 18 general circulation model (GCM)-based and hypothetical scenarios of climate change to a hydrologic model of the Sacramento River Basin. He used a two-part water balance model to estimate monthly runoff and soil moisture changes in the basin. His results suggest that winter runoff could increase substantially, and summer runoff might decrease under most of the scenarios. Summer soil-moisture levels might also decrease substantially. These changes are driven by higher temperatures, which decrease the amount of winter precipitation falling as snow and cause an earlier and faster melting of the snowpack that does form.

CALIFORNIA STUDIES IN THIS REPORT

Seven studies were completed as part of this regional study of the possible impacts of climate warming on California (Figure 14-4). These studies were quantitatively integrated as much as possible within the overall timeframe of this report to Congress to obtain as complete a picture of those impacts as possible. Also, several of the national studies have results pertaining to California. At the outset, it should be emphasized that most of these studies used existing models, and most evaluated potential climate change in terms of present demands, values, and conditions (including the current population and water delivery system).

Water is a key limiting resource in both managed and unmanaged ecosystems in the Central Valley Basin, and freshwater is important in estuarine ecosystems in the delta region. Consequently, the California studies were organized so that the impacts of climate warming on the entire hydrologic system could be examined, starting at subalpine lakes in the mountains surrounding the valley and finishing at the freshwater outflow into the delta region and estuary (Figure 14-4). The individual projects examined the potential impacts of climate change and sea level rise on particular ecosystems and water-delivery systems in the Central Valley (see Chapter 4: Methodology). One of the major goals of this regional study was to determine how much runoff would flow into the Central Valley from the surrounding mountains under different scenarios of climate change, how much of that runoff would be available for delivery to the water users in the state, and how much would reach the delta.

Analyses Performed for This Study

The following analyses were performed for this study.

- Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin - Lettenmaier and Gan, University of Washington, and Dawdy, consultant (Volume A)

The Lettenmaier et al. project is the first of a series of four projects designed to determine the impact of climate change on runoff and water deliveries within the Central Valley Basin (Figures 14-4 and 14-5). Their project was designed to estimate changes in runoff from the mountains to the water resource system in the floor of the valley. Lettenmaier et al. used data from climate scenarios supplied by EPA as input to their modeling studies. (See Chapter 4: Methodology, and the following section, California Regional Climate Change Scenarios).

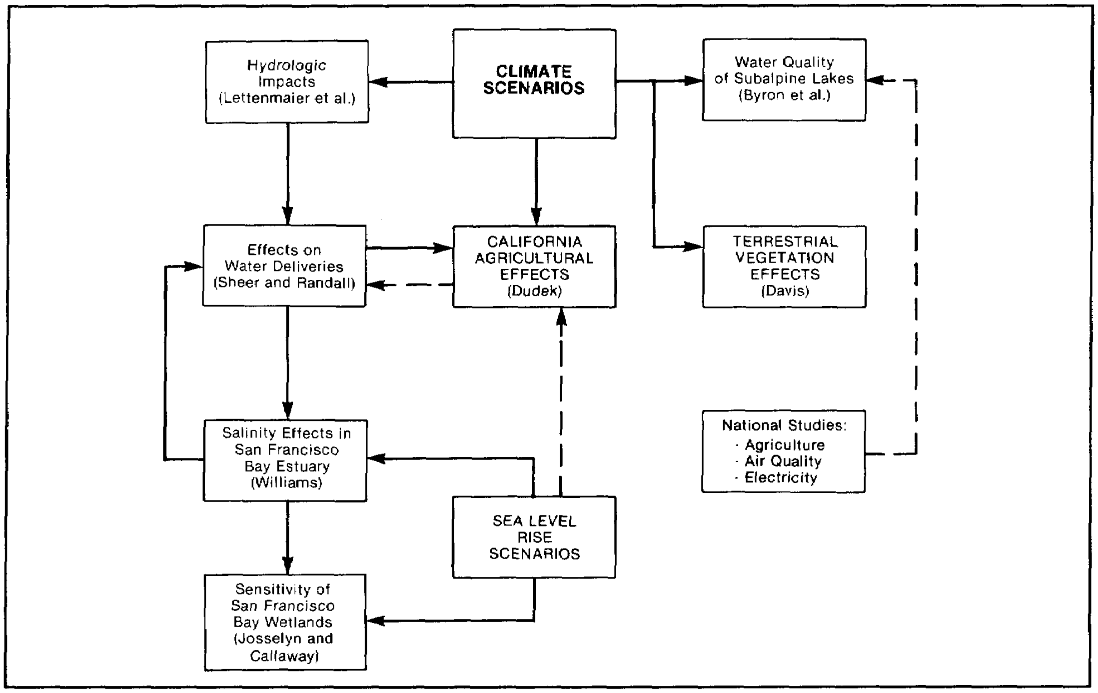

Figure 14-4. Organization of the study, showing paths of data input from scenarios and between projects (solid lines). Dashed lines indicate some important linkages between projects that were not quantitatively made in this study.

- Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the Water Supply Systems of the State of California and Atlanta, Georgia - Sheer and Randall, Water Resources Management, Inc. (Volume A)

Sheer and Randall used the projected runoff from the mountains determined by Lettenmaier et al. to simulate the response of the Central Valley and State Water Projects to climate change. Output from this study includes estimated total water deliveries to State Water Project users.

- The Impacts of Climate Chance on the Salinity of San Francisco Bay - Williams, Philip Williams and Associates (Volume A)

The main goal of Williams' project was to determine the impact of sea level rise and changing freshwater outflow into the delta on salinity within the bay. Williams also determined how much carriage water might be required to hold back salinity intrusions from the delta pumping plants after sea level rise. The new carriage water requirements were then factored into Sheer and Randall's simulation of the water resource system, and they represent an important feedback between the hydrologic effects of climate change and sea level rise effects in the delta (see Figure 14-3).

- Ecological Effects of Global Climate Change: Wetland Resources of San Francisco Bay - Josselyn and Callaway, San Francisco State University (Volume E)

Josselyn and Callaway used results from Williams and Park (see Chapter 7: Sea Level Rise) to assess the impact of changing salinity and sea level rise on the wetlands within San Francisco Bay.

- Climate Chance Impacts upon Agriculture and Resources: A Case Study of California - Dudek, Environmental Defense Fund (Volume C)

Dudek simulated the impact of changing climate on California agriculture. Besides using the climate data from the different climate scenarios to estimate crop productivity impacts, Dudek used estimates of mean annual water deliveries for deliveries for irrigation under the different climate scenarios as input to a regional economic model to estimate shifts in land and water use. This information was qualitatively used to compare available future water supplies and future water demand (see Figure 14-4). The ability of water policy changes to compensate for climate impacts was also evaluated.

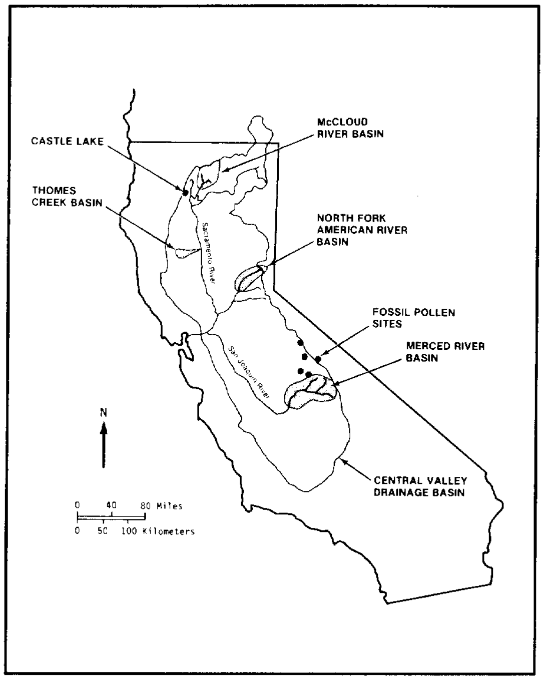

Figure 14-5. The Central Valley Drainage Basin of California. Shaded areas refer to the four study catchments used by Lettenmaier et al. Dots indicate the positions of the Castle Lake study site (Byron et al., Volume E) and the five fossil pollen sites (Davis, Volume D).

- The Effects of Global Climate Change on Water Quality of Mountain Lakes and Streams - Byron, Jassby, and Goldman, University of California at Davis (Volume E)

Byron et al. studied the impact of climate change on the water quality of a subalpine lake in northern California (see Figure 14-5).

- Ancient Analogs for Greenhouse Warming; of Central California - Davis, University of Arizona (Volume D)

Davis reconstructed the vegetation present in the Sierra Nevada during warm analog periods of the Holocene to estimate the potential impact of warming on the present-day vegetation in these mountains (see Figure 14-5).

National Studies That Included Results for California

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment - Adams and Glyer, Oregon State University, and McCarl, Texas A&M University (Volume C)

Adams et al. conducted a national study of agriculture to estimate shifts in land and water use. Results pertaining to California are discussed in this chapter.

- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates - Linder and Inglis, ICF, Inc. (Volume H)

As part of a national study, Linder and Inglis estimated future California electrical demands in response to climate change.

- Examination of the Sensitivity of a Regional Oxidant Model to Climate Variations -Morris, Gery, Liu, Moore, Daly and Greenfield, Systems Applications, Inc. (Volume F)

Morris et al. describe possible interactions of climate change and air pollution. Results pertaining to California are discussed in thus chapter.

CALIFORNIA REGIONAL CLIMATE CHANGE SCENARIOS

Results from two GCM gridpoints were used to drive the effects models used in most of the California studies. (For a discussion of how the scenarios were developed and applied, see Chapter 4: Methodology.) Both gridpoints lie at 120°W, with the northern gridpoint near the Oregon-California border and the southern gridpoint south of Sacramento (see Figure 14-1). Average temperature and precipitation changes for both gridpoints are displayed in Figure 14-6. Generally large seasonal increases in mean temperature are projected by the models. Winter temperatures are between 1.7°C (OSU) and 4.9°C (GISS) warmer, and summer temperatures are between 2.6°C (OSU) and 4.8°C (GFDL) warmer. The OSU model generally projects less warming than the other two GCM models.

Annual precipitation increases in GISS by 0.28 millimeters per day (4.02 inches per year) and remains virtually unchanged in the GFDL and OSU scenarios. Seasonal changes are more varied. For instance, spring rainfall in GFDL is 0.35 millimeters per day (0.41 inches per month) lower, while spring rainfall in the OSU and GISS scenarios is higher. The scenarios also show a large difference in fall precipitation (Figure 14-6).

Overall, the OSU scenario represents a smaller change from the present climate, and GFDL and GISS show larger temperature changes. The GISS scenario has higher precipitation than the other two scenarios. Generally, temperature increases are larger in the northern gridpoints than in the southern gridpoints. Changes in annual precipitation are greater in the north in GISS and show little regional difference for the other models.

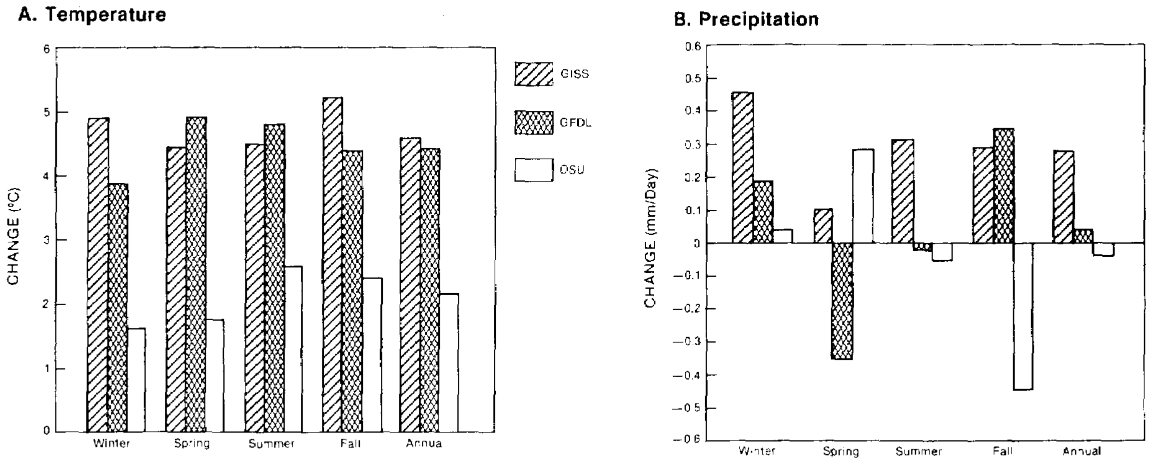

Figure 14-6. General circulation model (GCM) scenario results showing seasonal and annual (A) temperature and (B) precipitation changes between GCM model runs at doubled CO 2 and current CO_2 concentrations. The values are averages of the two gridpoints used by the water resource modelers. (See Figure 14-1 for the location of the gridpoints.)

RESULTS OF THE CALIFORNIA STUDIES

Hydrology of Catchments in the Central Valley Basin

Changes in mountain snowpack and runoff could have a major impact on water supply and quality in the Central Valley Basin. Lettenmaier et al. used a hydrologic modeling approach to simulate runoff under different climate scenarios; these estimates then served as input to the simulation of the Central Valley Basin water resource system response to climate change (Sheer and Randall, Volume A).

Study Design

The approach taken was to model the hydrologic response of four representative medium-sized catchments in the Central Valley Basin. Then streamflows for 13 larger sub-basins in the Central Valley Basin were estimated using the results from the four catchments. The four catchments chosen (see Figure 14-5) for modeling range in size from 526 to 927 square kilometers (203 to 358 square miles). Outflows for each basin were determined using two hydrologic models that estimate snow accumulation, ablation, and daily runoff. The models were calibrated using a subset of the historic record and were verified using an independent subset of the data.

Lettenmaier et al. developed an additional climate scenario besides those specified by EPA to test the sensitivity of their results to changes in the scenarios. The scenario they developed included only the GISS doubled CO temperature estimates; precipitation was kept unchanged from the current values. The purpose of this scenario was to determine the sensitivity of runoff to temperature changes alone.

To provide input for the water resource simulation model of Sheer and Randall (Volume A), Lettenmaier et al. developed a statistical model that relates historic flows in the four study catchments to historic flows in 13 larger subbasins in the Central Valley Basin. This statistical model was then used to estimate flows in the 13 subbasins under the different climate scenarios.

Limitations

Results would be different if geographic and temporal variability were not held constant within each grid. Several assumptions made in this study are important considerations in terms of limitations of the results. The intensity of rainfall is the same. Fewer rainfall events of higher intensity could increase runoff relatively more than a greater number of rainfall events of lower intensity. One implicit assumption is that no long-term changes in vegetation cover and composition would occur, when in fact such changes are virtually certain (but their hydrologic manifestations are difficult to predict). If vegetation cover decreases, runoff could increase, since less precipitation would be used by plants.

Lettenmaier et al. assumed that the flows into the water resource system were adequately estimated from the study catchment flows using their statistical model. One limitation of this model was that the study catchments are at high elevations and their runoff is strongly affected by changes in snowfall, whereas some of the areas contributing runoff to the water resource system are at lower elevations with runoff driven primarily by rainfall under present climatic conditions. Since the principal change under the scenarios was a change in snowfall accumulation patterns, the statistical model was biased toward these effects and may have somewhat overestimated the total effect of snowfall change on the water resource system. However, because basins at lower elevations have a relatively small impact on the total hydrology, thus bias minimally affected the results.

Despite these limitations, the results from thus study are qualitatively robust. Any improvement in the hydrologic modeling probably would not alter the general nature of the results, although their precision probably would increase.

Results

Total annual runoff from the four subbasins would remain about the same or increase slightly under the doubled CO_2 scenarios, but major changes occur in the seasonality of the runoff. Runoff could be higher in the winter months than it is today, because less of the precipitation would fall as snow and the snowpack could melt earlier (Figure 14-7A). As a consequence of higher early winter snowmelt, spring and summer runoff would substantially decrease under these scenarios. The variability of the runoff could substantially increase in the winter months. Winter soil moisture could increase; evapotranspiration could increase in the spring; and late spring, summer, and fall soil moisture could decrease. A major shift in the seasonality of runoff could occur in 50 to 75 years, according to the transient scenario GISS A.

When only temperature changes were incorporated into the climate scenario and precipitation was held equal to the base case, total annual runoff was estimated to be lower in all four catchments than in the scenario in which both temperature and precipitation were changed (Figure 14-7). However, the seasonal stuff in runoff, which is the dominant effect of a general warming, would be similar.

The scenario producing results that differed the most from the other scenarios was the 1930s analog. In this case, runoff was estimated to be lower in most months in the four subbasins, but the seasonal distribution of runoff was similar to the base case (Figure 14-7B). The reason for this difference is that the 1930s drought was mainly caused by a reduction in precipitation, rather than by an increase in temperature.

These results are consistent with those of Gleick (1987b), in that higher temperatures cause a major change in the seasonality of runoff. Since two different modeling approaches using many climate change scenarios produced similar results, these results can be viewed as relatively robust.

Implications

The potential change in seasonality of runoff could have significant implications for stream ecosystems and the water resource system in the Central Valley Basin. Reduction in streamflows in the late spring and summer could negatively affect aquatic organisms simply because of decreased water volume. Wildlife using streams for food and water also could be harmed. Water quality probably could be degraded because pollutants would become more concentrated in the streams as flows decrease. The possible impacts on the water resource system are discussed in the next section.

The decrease in spring, summer, and fall soil moisture could have a strong impact on the vegetation in the basin, with plants adapted to drier conditions becoming more abundant at the expense of plants adapted to higher moisture conditions. These potential vegetation changes also could affect wildlife, and perhaps water quality, through changes in the nutrient composition of upland runoff and changes in erosion rates.

Water Resources in the Central Valley Basin

Changes in runoff under the different climate scenarios could have a major impact on water resources in the Central Valley. The study by Sheer and Randall (Volume A) used estimates from Lettenmaier et al. of streamflows into the Central Valley to simulate how the water resource system would perform under the various climate scenarios. Particular emphasis was given to how water deliveries to users would be affected by climate change.

Study Design

To estimate the climate scenarios' impact on water deliveries, Sheer and Randall used an existing model of the California water resource system currently used by the southern California Metropolitan Water District (MWD) (Sheer and Baeck, 1987). The model emulates the State of California's Department of Water Resources Planning Simulation Model (California Department of Water Resources, 1986). The model used hydrologic inputs to project water-use demands, instream and delta outflow requirements, and reservoir operating policies. Water requirements were set at levels projected for 1990.

Two different sets of runs were made with the model. The first involved running the model for the different climate scenarios using current carriage water requirements. Williams (see the following section of this chapter, Salinity in San Francisco Bay) determined that in response to rising sea level and levee failure, carriage water might have to be doubled to maintain the water quality at the delta pumping plants (see Figure 14-2). Consequently, Sheer and Randall ran the model a second time to determine the effects of doubling the carriage water requirement on water deliveries. Both simulations were run with a monthly time step, with water deliveries summarized on a yearly basis. Interannual variation was used as an indicator of delivery reliability.

Sheer held a meeting with representatives of

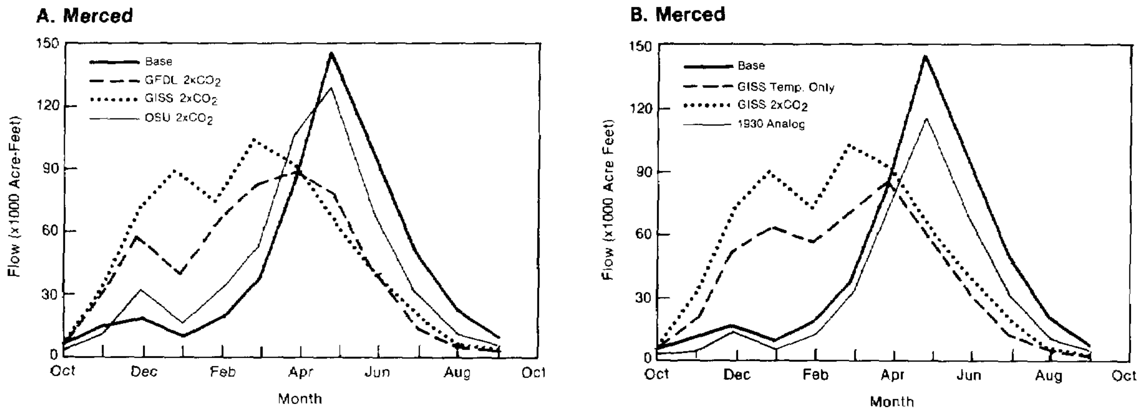

Figure 14-7. Mean monthly streamflows under difference climate scenarios for the Merced River Basin, one of the the four study catchments modeled (see Figure 14-5 for locations of the study catchments): (A) results from the three doubled CO_2 scenarios; and (B) results from the scenario incorporating only the temperature change projected in the GISS model run, and from the 1930s analog scenario (Lettenmaier et al., Volume A).

the California Department of Water Resources and the U.S. Bureau of Reclamation to discuss the results of his analyses and to obtain their responses on how the water resource system would handle the changes in runoff.

Limitations

The limitations to Lettenmaier's study carry over to this one. Thus, interpretation of the results of the simulation of the water resource system's response to climate change should focus on how the system deals with the change in seasonality of runoff, rather than on the absolute values of the model output. Also, the model was run using 1990 conditions, and changes in future management practices, operating rules, physical facilities, water marketing, agriculture, and demand were not considered in the simulation.

Results

The simulation results suggest that both the amount and reliability of water deliveries could decrease after global warming. The decreases in mean annual SWP deliveries were estimated to range from 7% (OSU) to 14% (GISS) to 16% (GFDL) (200,000 to 400,000 acre-feet) (Figure 148). In some years, the decreases would be over 20% for all three doubled CO_2 scenarios. The projected decrease in water deliveries occurs despite a slight increase in precipitation over current levels in the climate scenarios and greater total outflow from the delta. Deliveries to the CVP are not reduced under the scenarios. Average monthly outflow from the delta increases in the late fall and winter under the climate scenarios and is lower in the spring (Figure 14-9). In comparison, the state estimates that population growth and other factors will increase demand for SWP deliveries by 1.4 million acre-feet by 2010 (California DWR, 1983).

The driving factor behind this decrease is the change in seasonality of runoff. Higher winter temperatures could lead to more of the winter precipitation in the mountains falling as rain rather than snow, and also to an earlier melt of the snowpack. Consequently, more water would flow into the system during the winter, and less during the spring and summer. Given current operating rules and storage capacity, much of the higher winter runoff would be spilled from the reservoirs to maintain enough storage capacity to capture heavy runoff later in the rainy season and thus prevent downstream flooding. When the threat of floods decreases at the end of the rainy season in the spring and the reservoirs could be filled, runoff into the system would be reduced because of the smaller snowpack. Thus, total storage would be lower at the end of spring and water deliveries would be lower during the dry summer months. With system changes, the extra runoff could be stored. The shift in the seasonality of runoff and the response of the water resource system to that shift determine the changes in monthly delta outflow (Figure 14-9).

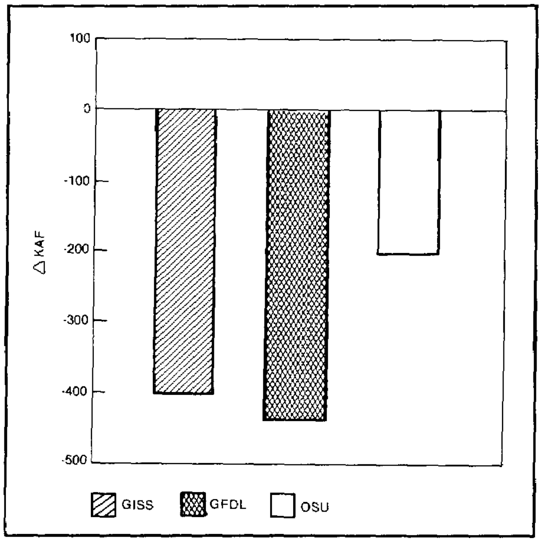

Figure 14-8. Mean annual change in SWP deliveries (base case minus scenario). KAF = thousands of acre-feet (Sheer and Randall, Volume A).

Doubling the carriage water requirement in the model run for the GFDL scenario would only minimally affect SWP deliveries. This is because the base period (1951-80) does not include a lengthy drought period, during which the doubled carriage water requirement could have a substantial impact on deliveries.

The consensus of the meeting of the representatives from the state DWR and the Bureau of Reclamation concerning the potential changes in seasonality of runoff was that the magnitude of this change would be such that operational changes alone would not markedly improve the system's performance. One factor limiting the potential for adjusting the system to the projected changes is the likely need to provide for additional flood control storage during the winter months because of higher peak flows.

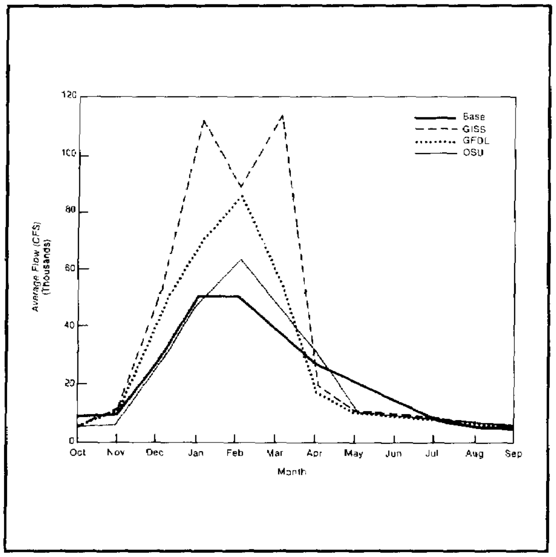

Figure 14-9. Projected monthly delta outflows under different general circulation model climate scenarios (adapted from Sheer and Randall, Volume A).

<u>Implications</u>

Under the three doubled CO_2 climate scenarios, water deliveries would be less than the base case and could fall short of 1990 requirements. Moreover, if carriage water requirements are doubled, shortages during a prolonged drought could become more significant. In comparison to these projected changes, the severe drought of 1977 reduced water deliveries by over 50% from the previous year. This decrease is over three times greater than those projected by Sheer and Randall. However, their study produced estimates of average changes, while the 1977 value reflects an extreme event over a short time period, which would have to be dealt with less frequently and in a potentially different manner than a more persistent shortfall in average supply. Also, Sheer and Randall did not consider future increases in water requirements caused by population increases and changes in the state's economy, which would exacerbate the projected water shortages. For instance, users and managers project a 55% (1.3 million acre-feet) increase in water required by SWP users in 2010 over the amount the system can reliably supply to them today (California Department of Water Resources, 1983).

The potential decrease in water deliveries could affect urban, agricultural, and industrial water users in the state. How the potential decrease should be managed has many policy implications, which are discussed at the end of this chapter.

On a positive note, the increase in delta outflow shows that more water could flow through the Central Valley Basin under these scenarios, and water deliveries could be increased if major new storage facilities were constructed. However, this would be an environmentally and politically controversial option (see Policy Implications section of this chapter).

Salinity in San Francisco Bay

Climate change could affect the San Francisco Bay estuary in two ways: first, changes in precipitation and temperature could affect the amount of freshwater runoff that will flow into the bay; and second, global warming could cause sea level to rise because of thermal expansion of the water and glacial melting, which could in turn affect a wide range of physical characteristics in the bay. The major objective of the study by Williams (Volume A) was to estimate the implications of global warming and rising sea level on the size and shape (morphometry) of the San Francisco Bay estuary and on salinity in the estuary.

Study Design

Williams' project was conducted in three parts, using two sea level rise scenarios and delta outflows estimated by Sheer and Randall (Volume A). The sea level rise scenarios are a 1-meter (40-inch) rise with the levees in the Sacramento-San Joaquin Delta and San Francisco Bay maintained, and a 1meter sea level rise with levee failure. The first part of this study involved estimating how sea level rise would affect the shape of the bay by establishing the elevation/area and elevation/volume relationships for all areas below + 3 meters (+ 10.0 feet) according to National Geodetic Vertical Datum (NGVD). In the second part of the study, the bay's tidal exchange characteristics were determined for its future shape by using a tidal hydrodynamic model (Fischer, 1970).

Finally in the third part of Williams' study, the bay's salinity under the combined impacts of sea level rise and changing delta outflows was calculated using a mixing model developed by Denton and Hunt (1986). This model was first run with nine different constant delta outflows (all months the same) to establish new carriage water requirements after sea level rise. (These requirements will also meet the state water quality standards for Suisun Marsh, as detailed in Water Rights Decision 1485.) Once these were established, and Sheer and Randall (Volume A) had run their simulation model with the new requirements, the mixing model was run again to determine the salinity regime in the estuary after climate change. Included in the model output were average monthly and average annual salinities in different parts of the estuary under the different scenarios.

Limitations

Because of the short time available for analysis, Williams used some old and inaccurate surveys in the morphometric analysis instead of making new surveys. These could produce errors of plus or minus 20% in the estimates of the estuary's volume. In addition, some levees probably would be maintained under any delta management plan, and thus the flooding of the delta islands would not be as extensive as assumed in the levee failure scenario. Williams did not consider changes in siltation and erosion of sediments that would likely occur under the different climate change scenarios. However, erosion would probably have a significant impact on water flow in the delta. For instance, deepening of the tidal channels in the delta could lead to intrusion of salinity farther upstream than projected in this study. In addition, more sophisticated models of salinity and tidal ranges and exchanges might improve the accuracy of the results. Finally, the new carriage water requirements were based on a steady-state analysis (e.g., constant delta outflows). Changes in the hydraulics of the Sacramento-San Joaquin Delta and Suisun Bay with sea level rise could increase these requirements. Williams' results should be viewed as a preliminary estimate of estuarine changes, with emphasis placed on the direction of change, rather than on the absolute amount of change.

Results

The morphometric analyses suggested that given a 1-meter (40-inch) sea level rise and failure of the levees, the total area of the estuary might triple, and its volume could double. If the levees are maintained, the increases in area and volume could be about 30 and 15%, respectively. The amount of sea level rise would be less important to the physical size of the bay than whether or not the levees are maintained.

Under the sea level rise scenarios with levees maintained, tidal ranges would not change significantly from current conditions. If the levees failed, downstream constrictions at Carquinez Strait and to the east of Suisun Bay (see Figure 14-2) would limit tidal transport and reduce tidal range in the delta, assuming that erosion does not alter the tidal characteristics of the delta.

The results from the initial application of the salinity model to constant delta outflows indicate that monthly carriage water requirements might have to be doubled to repel saline water from the upper part of the delta. Also, whether or not the levees are maintained would have little effect on the salinity regimes in the bay according to the model's results. However, because possible scouring of tidal channels was not incorporated into the model, the predicted salinity after levee failure is probably underestimated.

Using Sheer and Randall's estimated delta outflow with double carriage water, Williams also estimated annual salinity in the bay. The results suggest that after a climate warming, a 1-meter sea level rise, and failure of the levees, water of a given average annual salinity could migrate inland between 4 kilometers (2.5 miles) (GISS scenario) and 9.6 kilometers (6 miles) (OSU scenario) (Figure 14-10).

Williams also calculated the average monthly salinity for Suisun Bay for the three climate scenarios, levee failure, and double carriage water requirements. Monthly salinities would be higher for all months as compared with the base case, except for winter and early spring months in the GISS scenario. The greatly increased runoff of the GISS scenario (see Figure 14-9) during these months kept the salinity at the same level as the base case. Williams additionally modeled the frequency of a given salinity value in any month. In June, for example, salinities that were exceeded in 50% of the years in the base case might be exceeded in 80% of the years in both the GISS and OSU scenarios because of the lower outflows predicted under these scenarios.

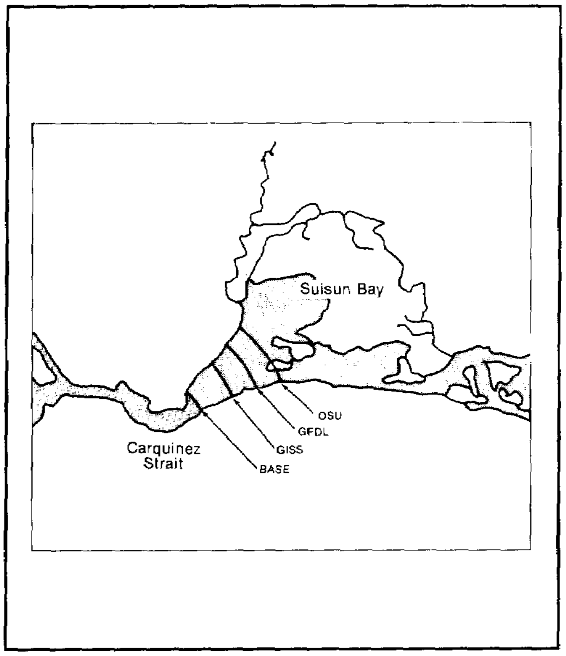

Figure 14-10. Movement of mean annual salinity of 10 parts per thousand under different hydrology scenarios. Other salinity levels move similar distances (see Figure 14-2 for location of Suisun Bay; Williams, Volume A).

Implications

Rising sea level could place the delta islands under increased risk of inundation, not only because of higher water levels but also because the larger area and volume of the San Francisco Bay estuary could result in greater wave energy and higher erosion rates of the levees. Improving the levees just to protect them against flooding at the current sea level could cost at least $4 billion (California Department of Water Resources, 1982). With higher sea levels, the cost of maintaining the levees would increase.

The large body of water created if all the levees failed would have a longer water residence time. This means that any contamination (salt or other pollutant) would be more difficult to flush out of the delta region. Also, if saline water fills the islands when levees fail, significant amounts of freshwater would be needed to flush out the salt.

Increasing salinity could necessitate increases in carriage water to maintain freshwater at the export point in the delta or could require developing a different method to convey freshwater from reservoirs to users. Assuming the current water management system is not expanded, the increase in carriage water coupled with the decrease in reservoir storage would most likely mean reduction in water deliveries to at least some of the system's users during extended droughts. With higher future water requirements, shortages caused by the higher carriage water requirements may not be limited to extended droughts. An increase in sea level could make navigation easier, temporarily reducing the need for dredging of navigation channels. On the other hand, a rising sea level could threaten fixed port terminals and piers.

Wetlands in the San Francisco Bay Estuary

Climate warming could alter two important physical factors that affect wetland distribution: sea level and freshwater outflow. Major impacts of sea level rise could include erosion and marsh inundation. Changes in freshwater outflow can change the distribution and productivity of estuarine plants and animals. Josselyn and Callaway (Volume E) estimated the possible effects of climatic warming on deep-water and wetland habitats of the San Francisco Bay estuary (see Figure 14-2).

Study Design

Josselyn and Callaway examined the impacts of a 1-, 2-, and 3-meter (40-, 80-, and 120-inch) sea level rise by the year 2100. Of the three scenarios, a 1-meter rise by the year 2100 is regarded as the most probable (NRC, 1987). Models were used to estimate rates of sea level rise from 1990 through 2100 under these three scenarios. The relationship between sedimentation rates required for marsh maintenance and sea level rise rates was examined. The effects of salinity changes on the distributions and abundances of organisms were related to various freshwater outflow scenarios developed by Sheer and Randall (see Figure 14-9). In the absence of appropriate quantitative models, biotic changes in the estuary in response to changing salinity were qualitatively determined based on literature review and expert judgment.

Limitations

Circulation and sedimentation in the estuary could change dramatically as sea level rises and if levees fail. The specific characteristics of these biologically important changes are unknown at present and were not considered in this study. The sea level rise scenarios did not consider the possibilities of sudden changes in sea level. Increased water temperature, which may directly affect the reproduction, growth, and survival of estuarine organisms, or may have an indirect effect through changes in oxygen availability, also was not considered. Although specific impacts on plant and animal species in the estuary are difficult to assess, the general impacts would most likely be similar to those reported here.

Results

Rates of sea level rise from 1990 to 2040 for the three scenarios are presented in Figure 14-11. Once the rate of sea level rise exceeds the rate of sediment accretion, tidal marsh habitats would become inundated and erosion of the marsh edge could increase. For the 1-meter rise scenario, the rate of rise was not estimated to exceed maximum accretion rates (7 to 8 millimeters per year) until about the year 2040. For the 2- and 3-meter (80and 120-inch) rise scenarios, the rate of sea level rise could exceed accretion rates after 2010 and 2000, respectively (Figure 14-11).

Peak primary productivity, at present, occurs in early spring in San Pablo Bay and in the summer in Suisun Bay. These maximum productivity levels could be substantially reduced, particularly for brackish and freshwater plant species, under the higher salinities of the OSU scenario (see Figure 14-10). Peak spring production might also shift upstream into the delta if levees fail. However, under the higher freshwater outflows of the GFDL and GISS scenarios, the locations of maximum production levels might remain in their present positions if the levees are maintained. If the levees fail, primary production could increase in the extensive shallow water and mudflat areas created.

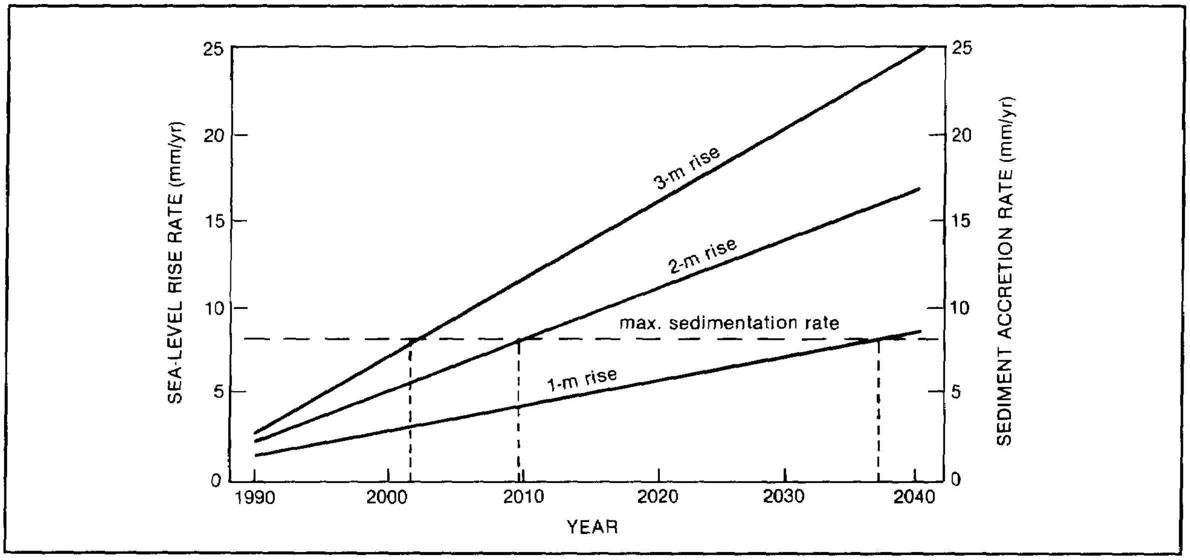

Figure 14-11. Estimated sea level rise at San Francisco for three scenarios by the year 2100 (Josselyn and Callaway, Volume E).

Since many areas currently protected by levees are 1 to 2 meters (40 to 80 inches) or more below sea level, levee failure would cause them to become deepwater areas rather than marshes (see Figure 14-3). Eventually, enough sediment might be deposited in these formerly leveed areas to support marsh development. Inundation of marshes and salinity impacts on freshwater and brackish-water plant species could reduce sources of food and cover for waterfowl. Loss of emergent vegetation could significantly reduce the numbers of migratory waterfowl using the managed wetlands along Suisun Bay's north shore.

If levees are maintained under conditions of sea level rise, salt may build up behind them from the evaporation of standing water. This salt would cause marsh vegetation to die back and reduce the value of these wetlands to wildlife.

Freshwater outflows estimated during springtime under the climate change scenarios (see Figure 14-9) may be too low to support anadromous fish (saltwater fish that enter freshwater areas for spawning). Lower outflows could result in declines among these populations (Kjeldson et al., 1981).

If levees failed, a large inland lake with fresh to brackish water quality could be created in the delta. Striped bass and shad spawn in essentially freshwater conditions and their spawning could be reduced under increased salinity, especially if they did not move upstream to relatively fresh water. Marine fish species could increase in abundance in the Suisun and San Pablo Bays in response to the projected higher salinities, and freshwater and anadromous species could decrease.

Implications

The loss of wetlands could result in substantial ecological and economic losses for the region. For example, the managed wetlands north of Suisun Bay support a hunting and fishing industry valued at over $150 million annually (Meyer, 1987). Tourism, hunting, fishing, rare and endangered species, and heritage values also could suffer.

California Agriculture

California's agricultural production is highly dependent on irrigation, which accounts for approximately 80% of the state's net annual water use. Dudek (Volume C) used existing agroecological models to explore potential responses of California agriculture to climate change.

Study Design

Climate changes from the GISS and GFDL doubled CO_2 scenarios were linked to an agricultural productivity model adapted from Doorenbos and Kassam (1979). Growth responses to both climate change and climate change plus direct effects of carbon dioxide were modeled. These productivity responses were then introduced into the California Agriculture and Resources Model (CARM) (Howitt and Mean, 1985), which estimates the economic and market implications of such changes. Mean surface water supplies under the base, GISS, and GFDL scenarios, calculated from the simulations of Sheer and Randall (Volume A), were also used as inputs into CARM.

Limitations

The CO_2 direct effects results should be viewed as preliminary, since they are based on data from growth chamber experiments that may poorly represent field conditions. This study did not consider changes in crop varieties, planting dates, energy costs, water-use efficiency, changes in the status of groundwater resources under a changed climate, or possible changes in delta agricultural acreage caused by flooding after levee failure. Also, new crop/location combinations were not considered, nor were changes in soil quality such as increases in salinity. The interaction between climate change and direct CO_2 effects on productivity were not examined but may significantly limit potential growth increases. The effects of climate changes on other agricultural production regions in the nation and the rest of the world were not considered. These could be major factors in determining how California farmers respond to climate change. Given these limitations, realistic estimates of agricultural responses to climate change may be difficult to obtain. The results may be more valuable as indications of sensitivity than as specific impacts.

Results

Relative to the 1985 base, yields could be significantly reduced for California crops in response to climate changes alone (i.e., without consideration of the direct effects of CO_2). Generally, the greatest impacts are estimated under the hotter GISS scenario. Table 14-1 presents regional yield changes for sugarbeets, corn, cotton, and tomatoes. These projections were generated by the agricultural productivity model and did not consider economic adjustments or water supply limitations. Tomatoes might suffer the least damage, with yields reduced by 5 to 16%. Sugarbeets could be hardest hit, with declines of 21 to 40%. Yield reductions in sugarbeets were estimated to be greatest in the relatively hot interior southern regions. Differences in growth response between the two climate scenarios are greatest for corn and least for tomatoes.

Without economic adjustments, corn yields are estimated to decline by 14 to 31%, based on the agricultural productivity model under the GISS scenario (Table 14-1). With economic adjustments, declines of roughly 15% were estimated, a result at the lower end of the direct productivity impacts.

When the direct effects of CO_2 on crop yields were considered, yields of cotton and tomatoes generally increased over the 1985 base (Table 141). Corn and sugarbeets were generally estimated to be unable to increase growth in response to increases in CO_2 oncentration, although yield reductions were not as great as with climate change alone (Table 14-1). Cotton could benefit the most from inadvertent CO_2 fertilization, with yields increasing in most cases by 3 to 41% (although under the GISS scenarios in the Sacramento Valley, they were estimated to decrease by 2%).

Potential increases in yields in response to CO_2 fertilization might be achieved only at a cost of increased groundwater extraction in many areas. For example, when surface water use was projected at 100% of capacity, as in the Central Coast regions, higher water requirements would necessitate increased groundwater usage (Figure 14-12). However, increased crop yields may offset increased economic costs of water.

Regionally, across all scenarios (not considering potential changes outside California) the largest reductions in crop acreage were projected in the Imperial Valley, while the delta region showed the largest gains in acreage (Figure 14-12). This expansion of agriculture in the delta region would depend on maintenance of levees protecting the farmland. Without a consideration of CO fertilization, statewide crop acreage was estimate to be reduced by about 4 to 6% from the 1985 base. When CO_2 direct effects were considered, statewide crop acreage was estimated to be

Table 14-1. Regional and Statewide Percentage Yield Changes (relative to 1985) Under Different General Circulation Model Climate Scenarios[a]

Region	Scenario	Crop							
		sugarbeets		corn		cotton		tomatoes	
		CC	Net	CC	Net	CC	Net	CC	Net
South Coast									
Los Angeles	GISS	-27	-3	-22	-18	-22	11	-8	17
	GFDL	-21	5	-3	3	-4	41	-5	20
North Interior									
Red Bluff	GISS	-34	-11	-17	-12	-30	3	-16	10
	GFDL	-26	0	-14	-9	-26	9	-14	12
Sacramento Valley									
Sacramento	GISS	-29	-3	-14	-9	-34	-2	-14	13
	GFDL	-24	3	-8	0	-32	2	-12	15
Southern San Joaquin									
Fresno	GISS	-34	-14	-19	-14	-29	6	-15	10
	GFDL	-32	-13	-13	-7	-26	11	-15	10
Southern Deserts									
Blythe	GISS	-40	-2	-31	-27	-28	6	-13	13
	GFDL	-39	0	-14	-8	-19	21	-12	15
CARM Statewide									
	GISS	-31	-8	-15	-10	-29	6	-14	12
	GFDL	-25	-1	-10	-4	-26	11	-13	13

[a] Regional changes were projected by the Doorenbos and Kassam agricultural productivity model, while statewide production changes were projected by the California Agriculture and Resources Model (CARM). The latter estimates included economic adjustment. "Net" includes the direct effects of increases in CO_2 and climate change (CC).

[b] Refer to Figure 14-12 for locations.

Source: Dudek (Volume C).

approximately equal with 1985 base levels.

Implications

Regional changes in cropping locations and patterns of water use imply potential exacerbation of existing nonpoint source pollution and accelerated rates of groundwater overdraft with ensuing environmental impacts.

Changing water supply requirements may result in increased conflicts between water users. In addition, shifts in the location of agricultural production could affect the future viability of natural systems. Such shifts could also have a significant impact on the economic health of small agricultural communities.

Regional Implications of National Agriculture Changes

Adams et al. conducted a national agricultural study that included results relevant to California (Adams et al., Volume C). The results of the study are not directly comparable with the results from Dudek's study (discussed above), since Adams et al. considered national agricultural impacts and aggregated California into a Pacific region with Oregon and Washington. Further, the two studies did not examine the same set of crops and modeled productivity differently. (For a description of the study's design and methodology, see Chapter 6: Agriculture.)

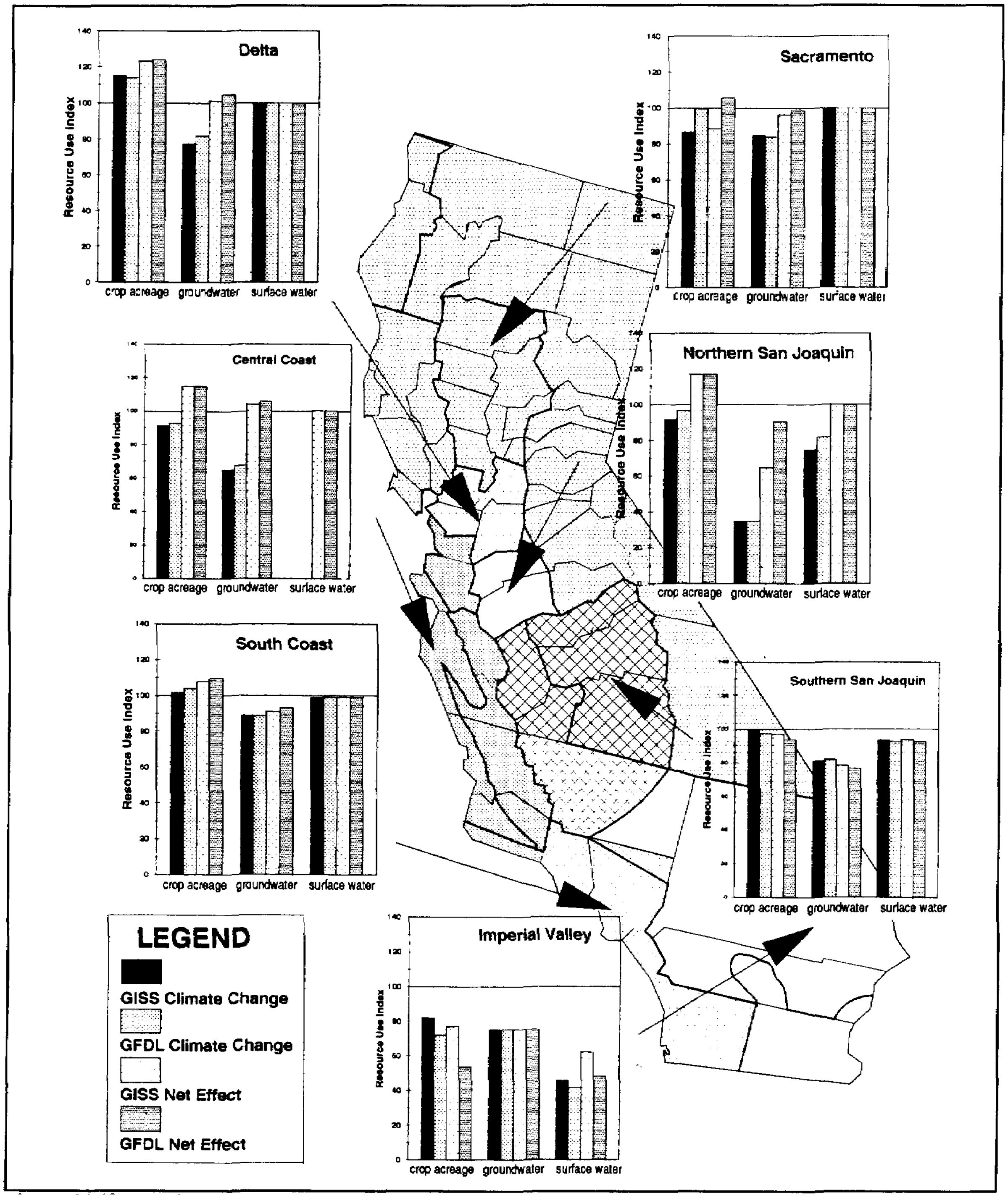

Figure 14-12. Regional crop acreage, groundwater use, and surface water use under different GCM climate scenarios. Net effect includes the direct effects of increases in CO_2 and climate change. The resource use indices represent the ratio (as percentages) of scenario results to the 1985 base period (Dudek, Volume C).

Results

Adams et al. (Volume C) estimated that national crop acreage could decline by 2 to 4% in response to climate change, but Pacific Coast State acreage could increase by 18 to 20%. This increase in the Pacific region is attributable to the region's extensive use of irrigated agriculture. In contrast, most other regions of the United States predominantly use dryland farming, and crop acreage might decline in response to moisture stress. The Adams et al. approach was based on maximizing farmers' profits and indicates that higher yields associated with direct CO_2 effects might result in further declines in crop acreage (or in the case of the Pacific Coast States, a smaller increase), since fewer acres might be required to produce the necessary crops.

Water Quality of Subalpine Lakes

Subalpine lakes are common in the California mountains, and many of these are the source of streams and rivers flowing down into the lowlands. Changes in the water quality of these lakes could significantly alter their species composition and nutrient dynamics and also could have an impact on downstream water quality and ecosystems. The sensitivity of California's subalpine lakes to weather variability and climate change has not been extensively studied. Consequently, Byron et al. studied how climate controls the water quality of Castle Lake, a subalpine lake in northern California (see Figure 14-5).

Study Design

Goldman et al. (1989) correlated an index of water quality, primary production (i.e., the amount of biomass produced by algae in the lake) with climate variability at Castle Lake. Subsequently, Byron et al. (Volume E) were able to develop empirical models relating primary production with various climate parameters.

Limitations

Their model was limited to estimating annual values of primary production; seasonal variability was not calculated. The model also did not project changes in species composition and nutrient dynamics, which could have important consequences for water quality. Changes in upland vegetation and nutrient cycling, which could also affect the lake's water quality, were not part of the model.

The estimates of annual primary production produced by this model are precise, although the results are general in the sense that no species specific projections are made.

Results

Byron et al. estimate that mean annual primary production could increase under all three doubled CO_2 scenarios, with increases ranging from 16% (OSU scenario) to 87% (GISS scenario) (Figure 1413). The OSU results are within one standard error of present production. Thus, under this scenario, there would be no significant decrease in water quality. The increase in annual primary production in the transient scenario was only statistically significant in the last decade of the transient scenario (2050-59). Primary production in the last decade was estimated to be 25% greater than the base case.

The increase in annual primary production is attributed principally to the temperature increase projected by the scenarios. The higher temperatures would result in less snow accumulation, which is correlated with an earlier melting of the lake ice and a longer growing season.

Implications

Higher primary production could result in climatic effects being indirectly felt at higher points in the Castle Lake food web and could affect the lake's nutrient dynamics.

Extrapolating these results to other subalpine lakes suggests their water quality could decrease and their species composition might change after climate warming. Increased primary production could provide additional food for other aquatic organisms, such as fish, but could also degrade water quality by ultimately causing a decrease in dissolved oxygen and by blocking light filtration to lower levels. Fisheries in unproductive lakes may be enhanced, although trout populations may suffer in lakes where temperatures rise past a threshold value and oxygen levels drop too low.

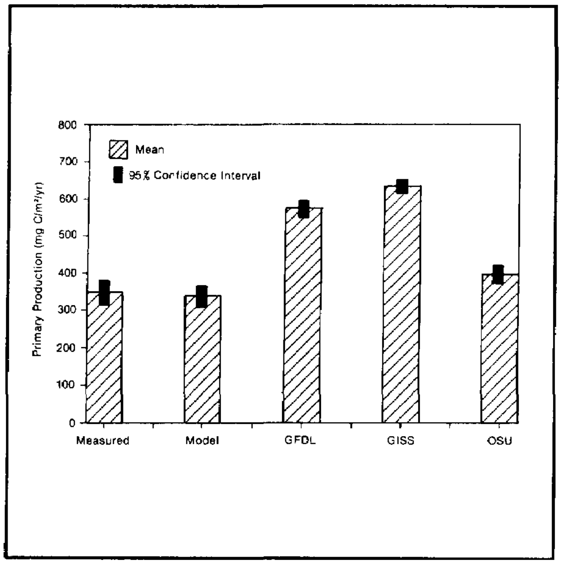

Figure 14-13. Annual primary production estimates for Castle Lake showing actual and model values for present conditions and model values for three GCM climate scenarios (see Figure 14-5 for the location of Castle Lake). Solid bars show the 95% confidence interval for each estimate (Byron et al., Volume E).

Changes in production and concomitant changes in nutrient dynamics could affect downstream river and reservoir water quality. However, since the streams draining subalpine lakes are well oxygenated, the increased biomass entering them would most likely be rapidly decomposed and probably would not affect the water quality of lower reaches of streams and rivers.

Summary of Effects on Water Resources

In terms of economic and social importance, changes in water resources are among the most important possible effects of climate change in California. A wide variety of factors related to climate change could affect water resources, ranging from those factors changing water supply to those affecting water requirements. All the individual projects discussed above addressed some aspect of climate impacts on water resources in the state. However, these studies did not consider all the major factors that could affect California water resources in the next century, mainly because of the complexity and inherent difficulties in forecasting future requirements for water. This section discusses other factors that would affect future water demands not directly considered by the individual studies, including future changes in agriculture, population, water-use efficiency, and sources of water, including groundwater.

Dudek's study used estimates of water deliveries from Sheer and Randall's study, but changes in agriculture that he determined, and hence changes in agricultural demand for water, are not factored back into the water simulation model. For instance, Dudek's results indicate that because of climate conditions, crop acreage in the Imperial Valley decreases, freeing water used there for irrigation to be used elsewhere in the state if water institutions permit such transfers. Also, as cropping patterns change, so does the pattern of needed water transfers via the water resource system, thus affecting water deliveries. Finally, Dudek found that groundwater usage can increase when the direct effects of CO_2 are included in his model. Estimated groundwater usage is projected to increase when full use of surficial water sources does not meet agricultural demands estimated in the model. Thus, Dudek's results suggest that agricultural demand for water could exceed surficial supplies after climate warming, further exacerbating water shortages.

Not considered in the overall California study, but critical to determining the magnitude of potential water shortages in the next century, are population growth and accompanying changes in water demands. Projections of population growth place the state's population at about 35 million in 2010 as compared with 24 million in 1980, an increase of 45% (California Department of Water Resources, 1983). As mentioned earlier, requirements for SWP deliveries by urban, agricultural, and industrial users could increase by 50% over what the system can reliably supply today. This shortfall by itself is significantly greater than the decrease in deliveries caused by the climate scenarios as determined by Sheer and Randall.

If water shortages become more common, agricultural, industrial, and residential users will probably change their water-use efficiency. Changes in efficiency could moderate possible future shortages. Any change in water pricing or water law also could affect water demand and supply, but these changes are very difficult to project far into the future.

Groundwater usage is discussed by Dudek, but the overall impacts of climate change on groundwater are not addressed in this project. As demand for water increases beyond the capability of the water resource system to deliver the needed water, mining of groundwater (as Dudek shows for agriculture) is one option users could adopt to meet their demand. Using groundwater could lessen the severity of water shortagesin the short term but presents environmental problems, such as land subsidence, over the long term.

In general, given the current water resource system, qualitative considerations of future changes in water requirements suggest that future water shortages could be significantly greater than estimated here for climate change alone.

Vegetation of the Sierra Nevada

To better understand the sensitivity of natural vegetation in California to climate change, Davis (Volume D) studied changes that have occurred over the past 12,000 years in terrestrial vegetation growing in the California Sierra Nevada. Changes in vegetation that occurred during this period suggest how the vegetation that currently exists in the mountains could respond to future climate changes. The middle latitudes of the Northern Hemisphere are believed to have been warmest (1 to 3°C warmer than today) about 6,000 years ago (Budyko, 1982), and parts of western North America were apparently warmest 9,000 years ago (Ritchie et al., 1983; Davis et al., 1986). Thus, the period between 6,000 and 9,000 years ago in California could present a possible analog to a warmer future climate.

Study Design

The composition of the vegetation that existed in the central Sierra Nevada over the last 12,000 years was determined using fossil pollen analysis. Fossil pollen samples were collected from five lakes situated along an east-west transect (see Figure 145) passing through the major vegetation zones of the Sierra Nevada. Dissimilarity values were calculated between modern and fossil pollen samples to determine the past vegetation at a particular site.

Limitations

The climate estimated in the three doubled CO_2 scenarios is different from the climate that probably existed between 6,000 and 9,000 years ago in the Sierra Nevada, according to Davis's interpretation of the region's vegetation history. Davis suggests that 9,000 years ago, the climate was drier than it is today. Whether it was warmer or cooler is uncertain. The climate 6,000 years ago was not much different from the modern climate. Thus, the analog climates are in marked contrast to the warmer climate estimated by all three GCMs for the gridpoint closest to the western slope of the Sierra Nevada. Also, the models suggest that total annual precipitation will not significantly change.Consequently, the results of this study do not provide an indication of how the present-day vegetation could respond under the climate scenarios constructed from the GCMs. Nevertheless, they do present a possible analog for how Sierra Nevada vegetation could respond to an overall warmer Northern Hemisphere climate that produces a drier but not significantly warmer Sierra Nevada climate.

Furthermore, the warming 6,000 to 9,000 years ago occurred over thousands of years, as opposed to the potential warming within a century. Thus, the analog does not indicate whether vegetation would be able to migrate and keep up with a relatively rapid warming.

Another constraint associated with using the past as an analog to trace gas-induced warming is that carbon dioxide levels were lower during the past 12,000 years than those projected for the next century. Higher carbon dioxide concentrations could partially compensate for adverse effects of higher temperatures and lower moisture levels on tree growth. The extent of this compensating effect is uncertain at this time. Nevertheless, the possibility exists that the magnitude of the vegetation change in the past to a warmer hemispheric climate could have been less if carbon dioxide concentrations had been higher.

A relatively small set of modern pollen samples was available for comparison to the fossil samples; therefore, the precision of the vegetation reconstruction is uncertain. Also, the precision of the estimated elevational shifts in the vegetation zones is low because of the limited number of fossil sites available for the analysis. Nevertheless, this study provides a good general summary of the vegetation changes in the Sierra Nevada during the past 12,000 years.

Results

The forests existing in the western Sierra Nevada 9,000 years ago resembled those found east of the crest today (Figure 14-14), with lower forest cover and tree density. Pine and fir densities, in particular, were lower. Between 9,000 and 6,000 years ago, the vegetation gradually became similar to the modern vegetation in the same area, and by 6,000 years ago the modern vegetation zones were established on both sides of the Sierra crest. The vegetation 6,000 years ago was subtly different from that in the area today, with less 6r and more sage. The forests may have been slightly more open than today.

Implications

If climate conditions of the Sierra Nevada in the next century become similar to those that existed 9,000 years ago, major changes could occur in forest composition and density. The vegetation changes could generate significant environmental impacts, ranging from changes in evapotranspiration and related hydrogeological feedbacks to changes in nutrient cycling and soils, which could degrade the water quality of mountain streams. Fire frequency could increase as a function of changes in fuel loads and vegetation. If dead wood rapidly builds up because of the decline in one or more tree species, large catastrophic fires could occur.

If future forests west of the Sierra crest become similar to current forests east of the crest, timber production could significantly decline. Based on inventory data from national forests, timberlands east of the crest currently support only about 60% of the wood volume of timberlands west of the crest (U.S. Forest Service, Portland, Oregon, personal communication, 1988). Different future climates could also necessitate changes in timber practices (e.g., reforestation techniques).

Vegetation change in response to climate change could produce additional stress for endangered animal species as their preferred habitats change. Populations of nonendangered wildlife also could be affected as vegetation changes.

Since the GCMs estimate a different future climate than the climate reconstructed for the analog period, it isimportant to consider how the vegetation in the Sierra Nevada could respond under the GCM-based climate scenarios as compared with the way it responded during the analog period. Recall that the climate in the GCMs is estimated to be significantly warmer than today's climate, with similar amounts of precipitation, while the analog climate was significantly drier with similar temperatures. One major difference in the impact of the two types of climate scenarios could be in the response of species at higher elevations in the Sierra Nevada. Since growing season length and warmth are generally considered to control the position of timberline (Wardle, 1974; Daubenmire, 1978), warmer temperatures under the GCM scenarios could be expected to raise the timberline. The timberline was not significantly higher during the analog period. Higher temperatures could also increase the elevation of other vegetation zones in the Sierra Nevada.

Another effect of higher temperatures in the GCM scenarios that would probably affect vegetation at all elevations is a reduction in effective moisture during the growing season. Lettenmaier et al. (Volume A), in fact, estimate such a decrease as soil moisture decreases in late spring, summer, and fall compared with the base case. Furthermore, for lower elevations at least, the growing season could be effectively shortened because of the earlier onset of moisture stress after winter rains. One result of this could be the extension of grasslands and chaparral higher up the slopes of the Sierra Nevada. Also, reduced moisture availability could alter the outcome of competition between plant species with different growth forms and longevity, thus changing the composition of the vegetation zones. Plant species with drought-resistant characteristics would probably increase in relative abundance. One possible consequence of this shift in species abundance is the formation of plant communities that resemble in some aspects plant communities that occurred 9,000 years ago. However, the complicating factor of more direct effects of higher temperatures makes such a projection uncertain, as does the lack of consideration of the direct effects of increasing concentrations of carbon dioxide.

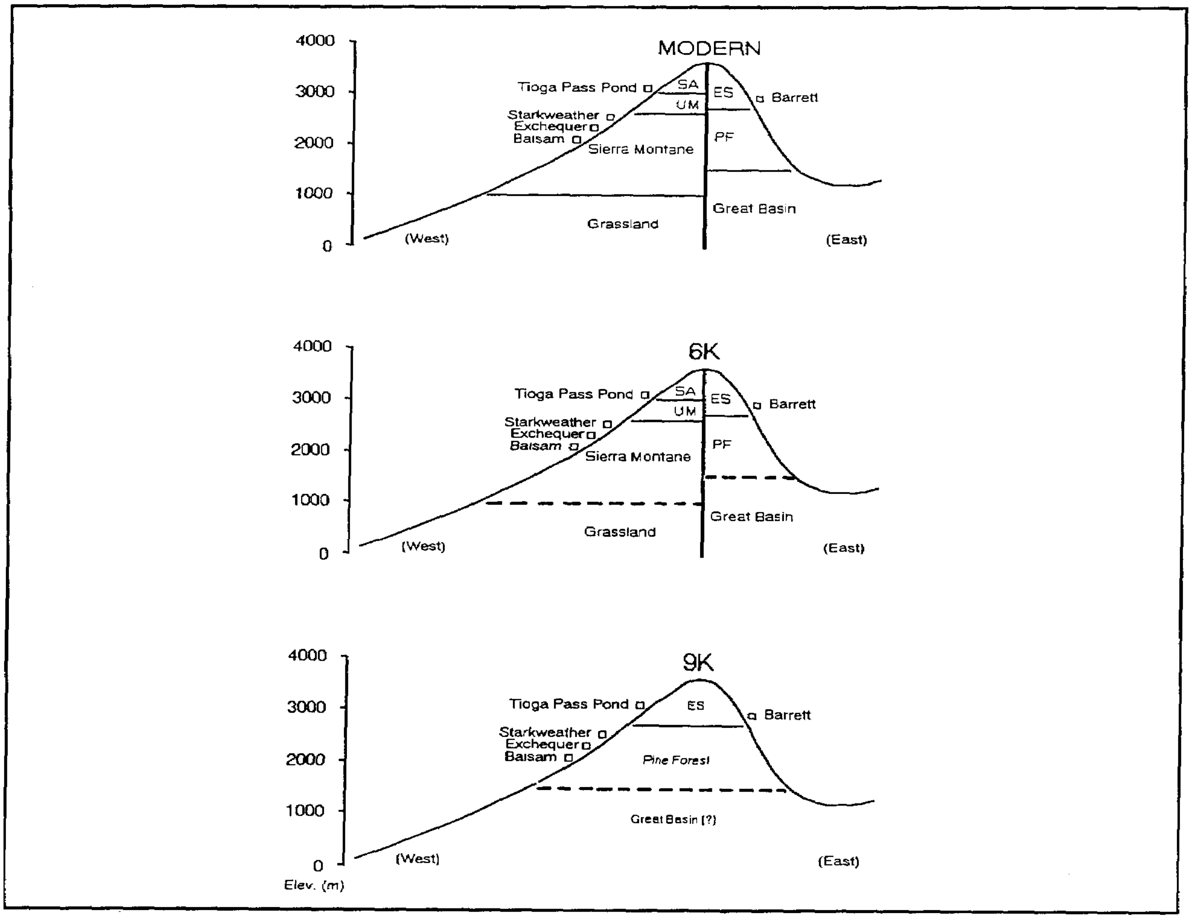

Figure 14-14. Vegetation zonation in the central Sierra Nevada at present; 6,000 years (6K) before present; and 9,000 years (9K) before present. (See Figure 14-5 for approximate locations of fossil pollen sites.) The dashed lines indicate uncertainty in the placement of vegetation zone boundaries (Davis, Volume D). SA = subalpine; UM = upper montane; ES = eastern subalpine; and PF = pine forest.

Electricity Demand

Electric power demand is sensitive to potential climate change. As part of a national study, Linder and Inglis estimated California's energy demand for the years 2010 and 2055. (For a description of the studs design and methodology, see Chapter 10: Electricity Demand.)

Results

In California, climate change scenarios result in only small changes in estimated electrical utility generation and costs by the year 2010. Annual power generation is estimated to increase by 1 to 2% (over the 345 billion kWh estimated to serve the California population and economy in 2010), and new generation capacity requirements would be less than 1% greater than increases without climate change. By the year 2055, annual power generation is estimated to increase by 3% under lower growth of electricity demand (604 billion kWh base) to 5% under higher growth (794 billion kWh base). New generation capacity requirements would be 14 to 20% greater than non-climate-induced needs. Then cumulative investments in new capacity could cost $10 to $27 billion (in 1986 dollars).

Implications

More powerplants may be required. These would need more cooling water, further depleting the water supply. Climate-induced changes in hydrology may reduce hydropower generation and increase dependence on fossil fuels and nuclear power. Increased use of fossil fuels may provide positive feedback for the greenhouse effect and may deteriorate local air quality. The increased utility rates that may be required to pay for new power generation capacity may limit groundwater pumping for agriculture.

Air Pollution

Morris et al. (Volume F) studied possible interactions of climate change and air pollution in California. They estimated the impacts of climate change on ozone concentrations using a regional transport model. The values they calculated should be viewed as coarse approximations because of the limitations in the application of the model. For instance, the study looked only at changes in temperature and water vapor and kept as unchanged many other important meteorological variables. An important unchanged variable was mixing height. Instead of remaining unchanged, mixing height could increase with rising temperatures. This would have a dilution effect on air pollution. (The study's design limitations and methodology are discussed in Chapter 11: Air Quality.)

Results

Morris et al. estimated that ozone concentrations could increase up to 20% during some days in August in response to a 4°C (7°F) climate warming in central California. The National Ambient Air Quality Standard (NAAQS) for ozone is 12 ppm. Morris et al. estimated that the number of August days that exceed this standard could increase by 30%. Furthermore, the area exceeding the NAAQS could increase by 1,900 square kilometers (730 square miles), and the number of people exposed to these elevated ozone levels could increase by over 275,000.

Implications

Trace gas-induced climate change may significantly affect the air's chemistry on local and regional scales. These changes may exacerbate existing air quality problems around California metropolitan areas and agricultural areas of the Central Valley, causing health problems and crop losses. Increases in air pollution may directly affect the composition and productivity of natural and managed ecosystems.

POLICY IMPLICATIONS

An overall question applies to resource management in general: What is the most efficient way to manage natural resources? Currently, management is based on governmental jurisdiction with, for example, forests managed at the local, state, or federal level. Management of hydrologic systems is also based on governmental jurisdiction. An alternative would be to manage these systems using natural boundaries as the criteria for determining management jurisdiction. The pros and cons of such a management strategy deserve at least some preliminary research.

Water Supply and Flood Control

Water supply is the basis for most economic development in California. Yet, almost all the water available in the SWP is allocated for use. A major problem is to accommodate rising demand for water, interannual climate fluctuations, and the need to export water from northern to southern California.

In addition, the results from these studies suggest that climate change over the next 100 years could cause earlier runoff, thus reducing water deliveries below their projected 1990 level. This situation (together with increasing requirements for water caused by increasing population) would create a set of major policy problems for the water managers and land-use planners in California.

Two major policy questions can be raised concerning the possible reduction in water deliveries: How can the water resource system be changed to prevent a decrease in water deliveries caused by climate change? If water deliveries fall short of demand, how should potential water shortages be allocated?

Approaches for Modifying the Water Resource System

Several possible approaches can be attempted to increase water deliveries. First, system management can be modified. For instance, the most recent SWP development plan suggests the possibility of state management of both SWP and CVP facilities (California Department of Water Resources, 1987a). Complete joint management could produce more than 1 million acre-feet (maf) additional reliable yield in the system. Steps toward greater cooperation have been taken. The Coordinated Operating Agreement (H.R. 3113) between the SWP and the CVP, ratified in 1986, allows the SWP to purchase water from the CVP. Using conservation techniques and improving the efficiency of transfer might also increase water deliveries.

Operating rules for the reservoirs also could be modified to increase allowable reservoir storage in April, which would increase water storage at the end of the rainy season and deliverable water during the peak demand season in midsummer. However, an increase in storage in the late winter and early spring would likely reduce the amount of flood protection (increase the risk of flooding) in the region; this in itself could negatively affect owners of floodplain property. Floods also place the delta islands at risk because of higher water levels. The tradeoff between water supply and flood control in northern California represents a potentially serious policy conflict affecting all levels of government in the region. In fact, the meeting between representatives of the State DWR and Bureau of Reclamation, which was held to discuss Sheer and Randall's results (Volume A), concluded that any likely changes in reservoir operation that would avoid a significant loss of flood safety would most likely bring about little improvement in the system's performance under the given climatic scenarios. Detailed study of this point is needed, however.

The second approach to maintain or increase water deliveries might be to construct new water management and storage facilities. However, trends over the past decade have shifted away from planning large physical facilities (e.g., the Auburn Dam and Delta Peripheral Canal). Building new facilities is expensive and raises serious environmental concerns about such issues as wild and scenic rivers. Another option is to use smaller facilities, such as the proposed new offstream storage facility south of the delta, and to improve the delta's pumping and conveyance facilities. With the help of these facilities, the SWP plans to achieve a 90% firm yield (the amount that can be delivered in 9 out of 10 years) of about 3.3 maf by 2010 (California Department of Water Resources, 1987a). Another relatively inexpensive option for off-line storage is artificial recharge of groundwater during wet years. The SWP is currently pursuing a proposal to deliver surplus water to groundwater recharge areas in the southern Central Valley to provide stored water for dry years.

The third approach to increase water deliveries is to turn to other sources of water. For instance, use of groundwater could be increased. However, in many metropolitan areas, groundwater bodies are currently being pumped at their sustainable yields. Any increase in pumping could result in overdraft. Furthermore, decisions to use groundwater are made by local agencies and/or individual property owners, and groundwater is not managed as part of an integrated regional water system. Whether or not to include it in the system is an important policy issue.

Another option is for southern California to choose to fully use its allotment of Colorado River water (which could lead to conflicts between California and other users of that water, especially Arizona). Other possibilities include desalinization plants, cloud seeding over the Sierras, and reuse of wastewater. However, desalinization plants are energy intensive and may exacerbate air quality problems. Also, cloud seeding is controversial, since downwind users may not be willing to lose some of their precipitation.

Options for Allocating Water Shortages

The second major policy question is how best to allocate potential water shortages. One way would be to allow greater flexibility in water marketing. The adverse effects of this policy change (e.g., perhaps water becoming too expensive for agriculture and possible speculative price increases) could be ameliorated through a variety of governmental policies. Yet, even with regulation, any changes in the current system along these lines would most likely be very controversial.

A second way to allocate the shortages is to rely on mechanisms used in the past to deal with droughts and water shortages, specifically governmental restrictions on water use. In the past, these mechanisms have included increased use efficiency, transfers of agricultural water to municipal and industrial uses, and restrictions on "nonessential" uses of water (e.g., watering of lawns). Increased efficiency of water usage through various conservation techniques could effectively increase the number of water users without actually increasing the amount of water delivered. If climate gradually changed and water shortages became more common, these restrictions could become virtually permanent.

Sacramento-San Joaquin River Delta

The delta area of the Sacramento and San Joaquin Rivers in the San Francisco Bay estuary receives great attention from governmental bodies at all levels because of its valuable agricultural land, its crucial role in the state's water resource system, and its sensitive environment. The results of the studies in this overall project suggest that this region could be significantly affected by climate change. Major changes could occur in delta island land use and in the water quality of the San Francisco Bay estuary. The policy implications of these possible changes are discussed below.

Delta Island Land Use

A critical land use issue is whether to maintain the levees surrounding islands threatened by inundation. Much of the land present on these islands is below sea level and is usable for agriculture, recreation, and settlement only through levee protection.

The individual delta islands have a significant range of values. For example, some islands contain communities and highways, and others are strictly agricultural. The property value of the islands is about $2 billion (California Department of Water Resources, 1987b). The islands also help repel saline water from the delta pumping plants (see Figure 14-2).

The levees have been failing at an increasing rate in recent years, and further sea level rise could increase failure probability. Improving the levees to protect the islands from flooding at the existing sea level and flood probability would cost approximately $4 billion (California Department of Water Resources, 1982).

The issue of levee failure raises three important policy questions. First, will some or all of the levees be maintained? The range of options concerning the levees includes inaction, maintenance of the status quo, strategic inundation of particular islands, and construction of polder levees.

Inaction, meaning the levees would not be improved with time, could eventually lead to the formation of a large brackish-water bay as all of the levees failed. Williams (Volume A) suggests that the area of the San Francisco Bay estuary could triple if all the levees failed.

Currently, the general policy is to maintain the delta's configuration. One important policy favoring the maintenance of the levees is the Delta Levee Maintenance Subventions Program, in which state financial assistance is available for maintaining and improving levees. The value of the islands for agriculture and maintenance of water quality (see below) has created additional institutional support for maintaining the levees, even though the cumulative cost may exceed the value of the land protected. Future funding decisions for this and related programs should consider the possibility of climate change. If the levees are maintained, an important policy question must be considered: Who will pay for the maintenance?

Not all the islands are equal with regard to their value in protecting the freshwater delivery system. A possible future policy response to rising sea level would be to maintain only certain levees and not reclaim other islands as they became flooded. In essence, this would be a strategic inundation policy. Some precedence exists for this policy, as Mildred Island was flooded in 1983 and not reclaimed; the high cost of reclaiming the island relative to its value was cited as a rationale.

Construction of large levees similar to the polders in Holland is an option for protecting the islands and maintaining shipping channels. However, this approach would be expensive and, although it has been discussed, has not attracted much serious attention.

The second policy question concerns failure of the levees. If all or some levees are allowed to fail, will landowners be compensated? If so, where will the money come from? The delta islands contain some of the most valuable agricultural land in the state. Loss of this land would be a severe economic hardship for the local farmers and for the associated business community. Whether these farmers should be compensated for their loss is an important public policy issue.

A final policy question remains: How will management of the delta islands be coordinated? Four government bodies have jurisdiction over the islands at the local, state, and federal levels. These bodies will need to coordinate activities to reach decisions regarding the future of individual delta islands.

<u>Water Quality of the San Francisco Bay Estuary</u>

The intrusion of saline waters into the upper reaches of the San Francisco Bay estuary could be a major problem in a warmer climate. Climate change is projected to cause increased salinity in the estuary, largely as a result of sea level rise, levee failure, and the inadequacy of freshwater outflow to offset the increase in salinity. Furthermore, land subsidence due to groundwater extraction could augment sea level rise. In some areas of the estuary, subsidence up to 1.5 meters (59 inches) has occurred within the past 40 years (Atwater et al., 1977).

Maintenance of current salinity levels is addressed in the water right Decision 1485 (D-1485) of 1978. This decision requires that water quality standards in the delta be maintained. If they are not, additional water must be released from reservoirs to improve delta water quality, which could reduce the amount of water available for delivery. Current policy does not explicitly take into account the potential for future climate change. Thus, D-1485 could be interpreted as requiring maintenance of delta water quality standards even if sea level rises and causes further penetration of saline water into the delta. Delta water quality standards are currently being reviewed at the BayDelta Hearing in Sacramento, which began in mid1987 and is expected to continue for 3 years. The choice of future options will be greatly affected by decisions made at the hearing.

Possible methods of combating the impacts of saltwater intrusion include maintaining levees, increasing freshwater outflows, reducing withdrawals, enlarging channels, constructing a barrier in the Carquinez Strait or lower delta, and/or constructing a canal around the delta's periphery. Alternatively, the freshwater pumping plants could be moved to less vulnerable sites. Decisions regarding response options will not be easily made. Levee maintenance and construction are costly. The water delivery agencies might be reluctant to increase delta outflows or to reduce withdrawals. Enlargement of delta channels, construction of saltwater barriers, and construction of a peripheral canal are extremely controversial environmental issues. Another possible response to these climatic impacts would be a gradual, planned retreat from the delta, devoting resources to options compatible with the absence of a freshwater delta. This response would also be very controversial, both politically and environmentally.

Water Quality of Freshwater Systems

The water quality of lakes, streams, and rivers could change as climate changes. Results from the Castle Lake study indicate that primary production of subalpine lakes could increase, with the potential for changes in the water quality of mountain streams (Byron et al., Volume E). Reduction in summer flows of streams and rivers in the Central Valley Basin could concentrate pollutants in these aquatic systems. A major policy question relates to these potential changes: How will potential reductions in water quality below levels mandated in the current Water Quality Act of 1987 (Public Law 100-4) be prevented?

Maintaining water quality despite decreased summer flows could be difficult and expensive. Controlling nonpoint source pollution is a goal of the Water Quality Act of 1987, and meeting this goal in the future could be more difficult and expensive because of the lower summer flows. Changes in land use near streams and rivers may be required to prevent runoff from agricultural land from reaching them. Reducing herbicide and pesticide use could also be another response, but this could harm agricultural production. Another option for preventing increased concentrations of pollutants in river reaches below reservoirs is to increase releases from reservoirs during summer months; this strategy would dilute the pollutants. However, this strategy would also have obvious negative impacts on water deliveries.

Municipalities that release treated sewage into rivers also could face increased difficulties in meeting water quality standards. Options include expanding sewage treatment facilities, which is expensive; releasing water from reservoirs to dilute the pollutants, as discussed above; or controlling the production of wastewater. Any municipalities planning for new sewage treatment plants should include climate change as one factor in the design criteria.

Reductions in summer flows could harm populations of aquatic organisms and terrestrial organisms that use riparian habitats. To the extent that these species become threatened with extinction, laws requiring preservation of endangered species (e.g., Endangered Species Act of 1973) may be invoked as a legal basis for increasing reservoir releases to preserve these species. This could place into conflict the governmental agencies and public constituencies concerned with preserving biodiversity and those concerned with the economic impacts on agriculture and industry.

Terrestrial Vegetation and Wildlife

Changing species composition and productivity might alter the character of forestry operations and the esthetic appeal of currently popular recreational areas. Climate-induced reductions in growth and regeneration rates, and increases in losses from wildfire and insect damage, could decrease the size and value of industrial forests in the state. How these changes would be managed is a complex question involving all levels of government as well as private landowners.

One major step in response to possible future climate change is to incorporate climate considerations into current planning processes. Federal planning for the effects of climate change on forests is discussed in Chapter 5: Forestry. Similar changes in the planning process could be considered at other levels of government. Coordinating the actions of government agencies involved with land management to climate change in California is another possible response.

The flora and fauna in California are highly diverse and include many rare and endangered species. Climate could change faster than some species could adapt, leading to local extinction of these species. Species conservation (as mandated by the Rare and Endangered Species Act of 1973) might require habitat reconstruction and/or transplanting in some situations. Monitoring programs may need to be instituted to track trends in populations and communities. Extensive programs have been developed for currently endangered species in the state (e.g., the California condor), and similar efforts probably could be mounted in the future for other highly valued species.

Agriculture

Changes in water availability and temperature stresses are projected to affect agricultural production. How will changes in agricultural production and crop types be managed, and how will California agriculture respond in national and international settings? (For further discussion, see Chapter 6: Agriculture.)

Historically, agriculture has quickly adapted to climate fluctuations. New technology and reallocation of resources might offset the impact of changed climatic conditions and water availability. Improved farm irrigation efficiency, such as extensive use of drip irrigation, could mitigate the impact of water-delivery shortages. Water marketing may provide a cost-effective means of meeting water demands and providing market opportunities for conserving water (Howitt et al., 1980). For example, water marketing may provide rights holders with the financial ability to invest in water conservation programs to cope with climate warming impacts on water availability.

Changes in cropping locations and patterns of water use could exacerbate nonpoint source pollution and accelerate rates of groundwater overdraft. Furthermore, changing water supply demands may heighten the conflicts between water allocation strategies and ecosystem and wildlife values.

It is uncertain how agricultural effects would be manifest in California's evolving economic and policy environment. For example, increased commodity prices could mitigate the financial impacts of potential reductions in crop acreage and production.

Wetland Vegetation and Fisheries

Wetland species are valuable ecologically, esthetically, and economically (photography, hunting, fishing, etc.). With rising sea level, areas supporting shallow-water vegetation might be inundated and converted to deep-water habitats supporting different species. New shallow-water sites could be created by artificially adding sediment. This option features its own environmental impacts and would most likely be expensive. However, maintaining shallow-water vegetation is important not only to the conservation of plant species but also to migratory birds, which feed on such vegetation.

Salinity impacts on phytoplankton and fisheries might be controlled via levee maintenance coupled with increases in delta outflow.

Shoreline Impacts of Sea Level Rise

The California coast includes a diverse array of shorelines ranging from cliffs to sandy beaches. Erosion along these coastlines may increase as a consequence of sea level rise. Such erosion could substantially damage shoreline structures and recreational values. Preventing the erosion would be very costly. For example, protecting the sewer culvert of the San Francisco Westside Transport Project from potential damage caused by sea level rise may cost over $70 million (Wilcoxen, 1986). Sound planning for shoreline structures should consider future erosion that may be caused by sea level rise. (For further discussion of these issues, see Chapter 7: Sea Level Rise.)

The accumulation of sediment behind water project dams and the effects of diversion structures, dredging operations, and harbor developments have limited the sources of sediment for beach maintenance (particularly along the southern California coast). Individual landowners and institutions constructing such infrastructures should consider their effects on sedimentation processes. Only through artificial deposition of sand (primarily from offshore sources) have southern California beaches been maintained. Beaches provide recreational areas and storm buffers, and their maintenance will require a major and continued commitment.

Energy Demand

A warmer climate could affect both energy demand and supply. For instance, higher temperatures could cause increased cooling demands, and changes in runoff could affect hydroelectric power generation. Institutions in California that are involved with energy planning, such as the State Energy Resources Conservation and Development Commission, should begin to consider climate change in their planning efforts so that future energy demands can be met in a timely and efficient fashion.

Air Quality

Increasing temperatures could exacerbate air pollution problems in California, increasing the number of days during which pollutant levels are higher than the National Ambient Air Quality Standards. Devising technological and regulatory approaches to meet ambient air standards is currently a major challenge in certain regions of the state, and these efforts must be continued. Under a warmer climate, achieving air quality standards may become even more difficult. To ensure that air quality standards are met under warmer conditions, policymakers, such as EPA and the California Air Quality Board, may wish to consider possible climate changes as they formulate long-term management options for improving air quality.

REFERENCES

Atwater, B.F., C.W. Hedel, and E.J. Helley. 1977. Late Quaternary Depositional History, Holocene Sea Level Changes, and Vertical Crustal Movement, Southern San Francisco Bay. U.S. Geological Survey Professional Paper 1014. Menlo Park, CA: U.S. Geological Survey.

Atwater, B.F., S.G. Conard, J.N. Dowden, C.W. Hedel, R.L. MacDonald, and W. Savage. 1979. History, landforms, and vegetation of the estuary's tidal marshes. In: Conomos, T.J., ed. San Francisco Bay: The Urbanized Estuary. San Francisco, CA: Pacific Division, American Association for the Advancement of Science, pp. 347-386.

Barbour, M.G., and J. Major. 1977. Terrestrial Vegetation of California. New York: John Wiley and Sons.

Budyko, M.I. 1982. The Earth's Climate: Past and Future. New York: Academic Press.

California Department of Water Resources. 1982. Delta Levees Investigation. Bulletin 199. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1983. The California Water Plan: Projected Use and Available Water Supplies to 2010. Bulletin 160-83. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1985. California State Water Project. Typewritten brief. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1986. Operations Criteria Applied in DWR Planning Simulation Model. Memorandum report. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1987a. California Water: Looking to the Future. Bulletin 160-87. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1987b Sacramento-San Joaquin Delta Atlas. Sacramento, CA: California Department of Water Resources.

California Division of Forestry and Fire Protection, 1988. California's Forest and Rangelands: Growing Conflict Over Changing Uses. Sacramento, CA: Forest and Rangeland Resources Assessment and Policy Act Committee.

Conomos, T.J., R.S. Smith, and J.W. Gartner. 1985. Environmental setting of San Francisco Bay. Hydrobiologia 129:1-12.

Daubenmire, R. 1978. Plant Geography With Special Reference to North America. New York: Academic Press, Inc.

Davis, O.K., J.C. Sheppard, and S. Robertson. 1986. Contrasting climatic histories for the Snake River Plain result from multiple thermal maxima. Quaternary Research 26:321-339.

Denton, RA., and J.R. Hunt. 1986. Currents in San Francisco Bay. Final report. Berkeley, CA: University of California.

Doorenbos, J., and A.H. Kassam. 1979. Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. Rome: Food and Agriculture Organization.

Fernald, M.L. 1950. Gras Manual of Botany, 8th ed. New York: American Book Company. Fischer, H.B. 1970. A Method for Predicting Pollutant Transport in Tidal Waters. Contribution No. 132. Berkeley, CA: University of California Water Resources Center.

Gleick, P.H. 1987a. Regional hydrologic consequences of increases in atmospheric CO_2 and other trace gases. Climatic Change 10:137-161.

Gleick, P.H. 1987b. The development and testing of a water balance model for climate impact assessment: modeling the Sacramento Basin. Water Resources Research 23:1049-1061.

Goldman, C.R., A. Jassby, and T. Powell. 1989. Interannual fluctuations in primary production: impact of climate and weather at two subalpine lakes. Limnology and Oceanography. In press.

Howitt, R.E., D.E. Mann, and H.J. Vaux, Jr. 1980. The economics of water allocation. In: Englebert, EA., ed. Competition for California Water. Berkeley, CA: University of California Press.

Howitt, R.E., and P. Mean. 1985. Positive Quadratic Programming Models. Working Paper No. 85-10. University of California, Department of Agricultural Economics. Davis, CA: University of California.

Kjeldson, M.A., P.F. Raquel, and F.W. Fisher. 1981. Influences of freshwater flow on chinook salmon in the Sacramento-San Joaquin Estuary. In: Cross, R.D., and D.L. Williams, eds. Proceedings of the National Symposium on Freshwater Inflow to Estuaries, Vol. 2. Washington, DC: U.S. Department of the Interior, pp. 88-108.

Leverenz, J.W., and D.J. Lev. 1987. Effects of carbon dioxide-induced climate changes on the natural ranges of six major commercial tree species in the western United States. In: Shands, W.E., and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington, DC: The Conservation Foundation, pp. 123-155.

Macdonald, K.B. 1977. Coastal salt marsh. In: Barbour, M.G., and J. Major, eds. Terrestrial Vegetation of California. New York: John Wiley and Sons, pp. 263-294.

Major, J. 1977. California climate in relation to vegetation. In: Barbour, M.J., and J. Major, eds. Terrestrial Vegetation of California. New York: John Wiley and Sons, pp. 11-74.

Meyer, P.A. 1987. The value of wildlife in San

Francisco Bay. Exhibit 38. Entered by the Bay Institute of San Francisco to the State Water Resources Control Board in Sacramento, CA.

Miller, C.S., and R.S. Hyslop. 1983. California: The Geography of Diversity. Palo Alto, CA: Mayfield. Munz, P.A., and D.D. Keck. 1959. A California Flora. Berkeley, CA: University of California Press.

National Research Council. 1987. Responding to Changes in Sea Level. Committee on Engineering Implications of Changes in Relative Mean Sea Level. Washington, DC: National Academy Press.

Nichols, D.R., and N.A. Wright. 1971. Preliminary map of historic margins of marshland, San Francisco, California. U.S. Geological Survey Open File Map, San Francisco Bay Region Environment and Resource Planning Study. Basic Data Contribution 9.

Raven, P.H. 1977. The California flora. In: Barbour, M.G., and J. Major, eds. Terrestrial Vegetation of California. New York: John Wiley and Sons, pp. 109-137.

Ritchie, J.C., L.C. Cwynar, and R.W. Spear. 1983. Evidence from north-west Canada for an early Holocene Milankovitch thermal maximum. Nature 305:126-128.

Sheer, D.P., and M.L. Baeck. 1987. Documentation of the CVP/SWP Simulation Models Developed by WRMI. Columbia, MD: Water Resources Management, Inc.

Sudman, R.S.1987. Layperson's Guide to the Delta. Sacramento, CA: Western Water Education Foundation.

U.S. Bureau of Reclamation. 1985. Summary Statistics, 1984; Volume 1: Water, Land and Related Data. Denver, CO: U.S. Bureau of Reclamation, Division of Water and Land Technical Services.

U.S. Department of Agriculture. 1987. Agricultural Statistics 1987. Washington, DC: U.S. Government Printing Office.

U.S. Department of the Interior. 1986. National Forest Statement of Receipts, Fiscal Year 1986. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency. In preparation. Ecological Effects of Global Climatic Change. Chapter 4. In: U.S. EPA Global Climatic Change Program.

U.S. Maritime Administration. 1985. Containerized cargo statistics, 1983. Washington, DC: U.S. Government Printing Office.

Wardle, P. 1974. Alpine timberlines. In: Ives, J.D., and R.G. Barry, eds. Arctic and Alpine Environments. London: Metheun and Company, pp. 371-402.

Wilcoxen, P.J. 1986. Coastal erosion and sea level rise: implications for ocean beach and San Francisco's Westside Transport Project. Coastal Zone Management Journal 14:173-191.

CHAPTER 15
GREAT LAKES

FINDINGS

Global climate change could affect the Great Lakes by lowering lake levels, reducing ice cover, and degrading water quality in rivers and shallow areas of the lakes. It could also expand agriculture in the northern states, change forest composition, decrease regional forest productivity in some areas, increase open water fish productivity, and alter energy demand and supply.

Lakes

- Average lake levels could fall by 0.5 to 2.5 meters (1.7 to 8.3 feet) because of higher temperatures under the doubled CO_2 scenarios in this report. A drop of 1 meter would leave average levels below historic lows. Even if rainfall increases, the levels would fall because higher temperatures would reduce the snowpack and accelerate evaporation. The estimates of lake level drop are sensitive to assumptions about evaporation; under certain limited conditions, lake levels could rise.

- As a result of higher temperatures, the duration of ice cover on the lakes would be reduced by 1 to 3 months. Ice could still form in near-shore and shallow areas. Changes in windspeed and storm intensity would affect the duration of ice cover.

- Shoreline communities would have to make adjustments to lower lake levels over the next century. Hundreds of millions of dollars may have to be spent along the Illinois shoreline alone, dredging ports, harbors, and channels. Water intake and outflow pipes may have to be relocated. On the other hand, lower levels would expose more beaches, which would enhance shoreline protection and recreation.

- Climate change could have both good and bad effects on shipping. Lower lake levels may necessitate increased dredging of ports and channels or reduced cargo loads. Without dredging, shipping costs could rise 2 to 33% as a result of reduced cargo capacity. However, reduced ice cover would lengthen the slopping season by 1 to 3 months. Under scenarios of relatively smaller lake level drop (0.7 to 1 meter), the shipping season would be lengthened sufficiently to allow for the transport of at least the same amount of cargo. Under a scenario of larger lake level drops (1.65 meters) and no dredging, total annual cargo shipments could be reduced.

Water Quality and Fisheries

- Higher temperatures could change the thermal structure of the Great Lakes. The result would be a longer and greater stratification of the lakes and increased growth of algae. This result is very sensitive to changes in windspeed and storm frequency -- two areas of relative uncertainty. These two factors would combine to reduce dissolved oxygen levels in shallow areas of lakes such as Lake Erie. A study of southern Lake Michigan indicated that annual turnover of the lakes could be disrupted.

- Climate change could increase concentrations of pollutants in the Great Lakes Basin. Dredging of ports could suspend toxic sediments in near-shore areas. Potential reductions in riverflow in the basin would create higher concentrations of pollutants in streams. The disposal of toxic dredge spoils was not studied in this report.

- The effects on fisheries would be generally beneficial. Higher temperatures may expand fish habitats during fall, winter, and spring, and accelerate the growth and productivity of fish such as black basses, lake trout, and yellow perch. On the other hand, fish populations could be hurt by decreased habitats and lower dissolved oxygen levels during the summer. The effects of potential changes in wetlands due to lower lake levels, reductions in ice cover, introduction of new exotic species, and increase in species interaction were not analyzed, although they could offset the positive results of these studies.

Forests

- The composition and abundance of forests in the Great Lakes region could change. Higher temperatures and lower soil moisture could reduce forest biomass in dry sites in central Michigan by 77 to 99%. These mixed hardwood and oak forests could become oak savannas or grasslands. In northern areas such as Minnesota, boreal and cedar bog forests could change to treeless bogs, and mixed northern hardwood and boreal forests in upland areas could become all northern hardwoods. Productivity could decrease on dry sites and bogland sites, but it could increase on some well-drained wet sites. Softwood species that are currently commercially important could be eliminated and replaced by hardwoods, such as oak and maple, which are useful for different purposes.

- Depending on the scenario, changes in forests could be evident in 30 to 60 years. These results do not reflect additional stresses, such as pests and increased fire frequency, nor do they reflect the possible beneficial impacts of increased CO_2 levels.

Agriculture

- Considering climate change alone, corn and soybean yields in northern areas, such as Minnesota, could increase by 50 to 100% and could decline in the rest of the region by up to 60%. The combined effects of climate and higher CO 2 levels could further increase yields in the north and result in net increases in the rest of the region, unless climate change is severe.

- Agricultural production in the northern part of the region may expand as a result of declines elsewhere. However, the presence of glaciated soils in northern states could limit this expansion. Acreage in the Corn Belt states may change little. Wider cultivation in the north could increase erosion and runoff, and degrade surface and groundwater quality. Increased agriculture would require changes in the infrastructure base, such as in transportation networks.

Electricity Demand

- There could be little net change in annual electricity demand. In northern areas, such as Michigan, reduced heating needs could exceed increased cooling requirements, while in southern areas, such as Illinois, cooling needs may be greater than heating reductions. The annual demand for electricity in the entire region could rise by 1 to 2 billion kilowatthours (kWh) by 2010 and by 8 to 17 billion kWh (less than 1%) by 2055. This study did not analyze the reduced use of other fuels such as oil and gas in the winter, changes in demand due to higher prices, and the impacts on hydroelectric supplies. Previous studies have suggested that reduced lake levels and river flows could lead to reductions in hydroelectric power production.

- By 2010, approximately 2 to 5 gigawatts (GW) could be needed to meet the increased demand, and by 2055, 23 to 48 GW could be needed -an 8 to 11% increase over baseline additions that may be needed without climate change. These additions could cost $23 to $35 billion by 2055.

Policy Implications

- U.S. and Canadian policymakers, through such institutions as the International Joint Commission, should consider the implications of many issues for the region. This study raises additional issues concerning the following:

- The water regulation plans for Lake Ontario and possibly for Lake Superior lake levels.
- The potential increased demands for diverting Great Lakes water for uses outside the basin. Before such a potential demand could be accommodated, additional analysis would be required. This is not currently allowed by federal statutes.
- Long-range industrial, municipal, and agricultural water pollution control strategies. Agencies such as EPA may wish to examine the implications for long-term point and nonpoint water pollution control strategies.
- The research, planting, and land purchase decisions in northern forests by federal, state, and private institutions.

CLIMATE-SENSITIVE NATURAL RESOURCES IN THE GREAT LAKES REGION

The Great Lakes region' is highly developed, largely because of its natural resources. The steel industry developed along the southern rim of the lakes, in part because iron ore from the north could be inexpensively transported over the lakes. Rich soils, moderate temperatures, and abundant rainfall have made the southern part of the region a major agricultural producer. Forests are abundant in the north and support commercial and recreational uses. The basin has become the home of over 29 million Americans and produces 37% of U.S. manufacturing output (U.S. EPA and Environment Canada, 1987; Ray et al., Volume J).

Current Climate

The Great Lakes region[1] has a midlatitude continental climate. Winter is sufficiently cold to produce a stable snow cover on land and ice on the lakes. The average January temperature over Lake Superior is -15°C (5°F), and the average July temperature in the southern part of the region is 22°C (72°F). The average rainfall varies from 700 to 1,000 millimeters (27 to 39 inches), depending on location (Cohen, in Glantz, Volume J).

The Lakes

The Great Lakes consist of a system of five major lakes that contain approximately 18% of the world supply of surface freshwater and 95% of the surface freshwater in the United States (U.S. EPA and Environment Canada, 1987) (see Figure 15-1, Map of the Great Lakes). The natural flow of the lake system begins in Lake Superior, the largest of the lakes, which drains via the St. Mary's River into Lakes Michigan and Huron (considered a single hydrologic unit because they are connected by the Straits of Mackinac). Water from Lakes Michigan and Huron flows out through the St. Clair River into Lake St. Clair. From there, the water flows through the Detroit River and into Lake Erie, the shallowest lake. The Niagara River connects Lakes Erie and Ontario, and the system ultimately empties into the Atlantic Ocean via the St. Lawrence River and Seaway.

The greatest influence on lake levels is nature. Seasonal fluctuations are on the order of 0.3 to 0.5 meter (1 to 1.7 feet), with the lakes peaking in late summer because of condensation over the northern lakes and reaching minimum levels in late winter. Interannual lake level changes have been much larger, approximately 2 meters (6.6 feet).

Lake Regulation

The flow between the lakes is controlled by dams at two points: (1) the St. Mary's River to control

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[1] This chapter will cover only the U.S. side of the Great Lakes and the eight states bordering them (see Figure 15-1).

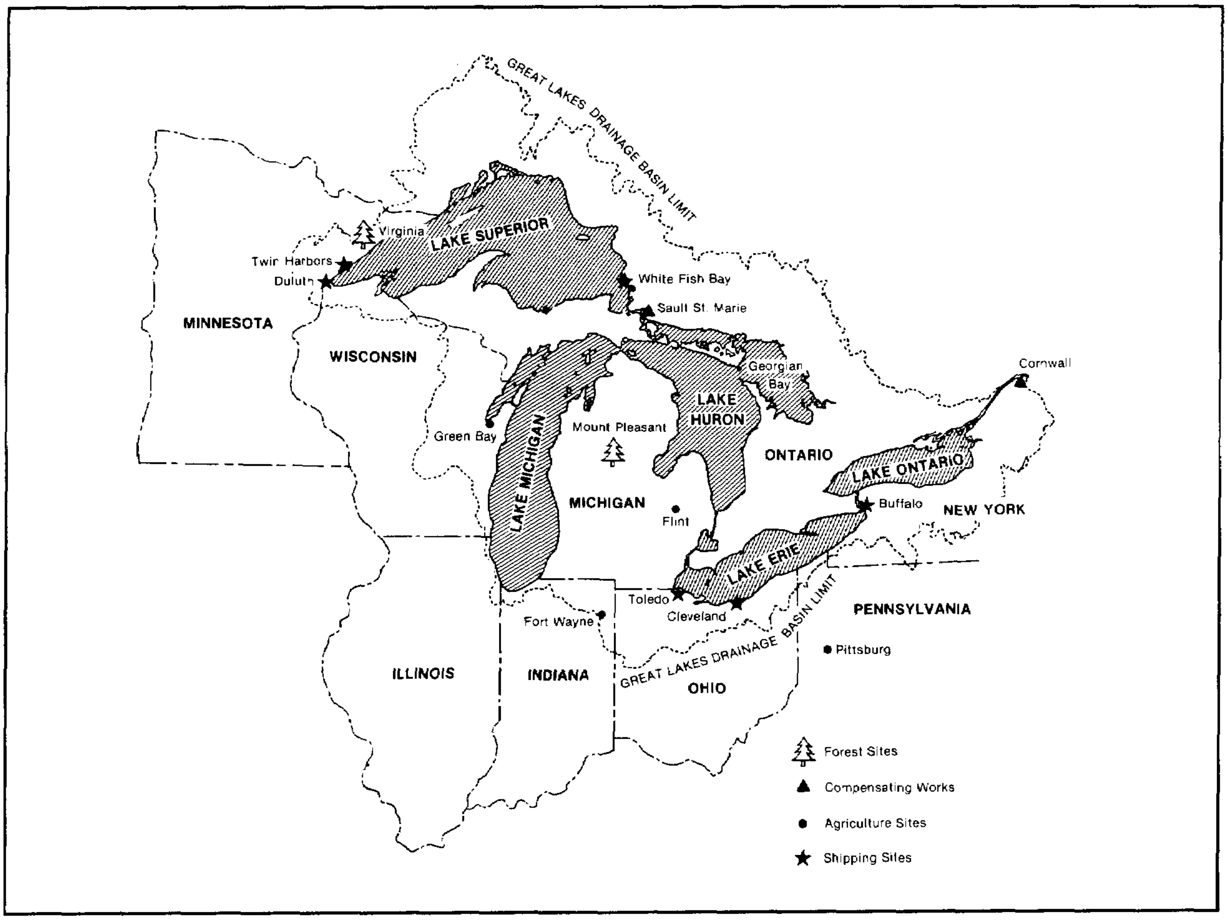

Figure 15-1. Map of the Great .Lakes study sites.

levels of Lake Superior; and (2) Iroquois, Ontario, to control Lake Ontario. The major diversion out of the lakes is the Chicago diversion, which transfers water from Lake Michigan through the Illinois River into the Mississippi River. Human influence on lake levels is relatively small. Doubling the flow down the Chicago diversion would lower lake levels only by 2.5 inches in 15 years (F. Quinn, Great Lakes Environmental Research Lab., 1987, personal communication).

Joint control of lake supply was codified in the Boundary Waters Treaty of 1909 between Canada and the United States, which created the International Joint Commission (IJC) consisting of representatives from both countries. The IJC regulates flow through the control structures and diversions by balancing the needs of shipping, hydropower, and consumptive uses among the lakes and along the St. Lawrence River and Seaway. Two regulatory plans (Plan 1977 for Superior and Plan 1958D for Ontario) set ranges of levels between which Lakes Superior and Ontario must be maintained. Diversion out of the lakes is also limited by law. Flow through the Chicago diversion was limited by the Supreme Court to 90 cubic meters per second (3,200 cubic feet per second) (Tarlock, 1988), and the 1986 Water Resources Development Act forbids diversion out of the lakes' basin without the consent of all Great Lakes governors (Ray et al., Volume J).

Climate-Sensitive Uses of the Lakes

Shipping

The U.S. Great Lakes fleet, which consists of approximately 70 ships, transported over 171 million tons of cargo in 1987 (The New York Times, 1988). The tonnage of U.S. shipping consists of iron ore, coal, and limestone, all primary inputs for steel (77%); lake grain (13%); and petroleum products, potash, and cement (10%) (Nekvasil, 1988). Cargo volumes are displayed in Table 15-1. Most of the goods are shipped within the Great Lakes, with only 7% of the tonnage (mainly grains) slopped to overseas markets (Ray et al., Volume J). Although shipping activity had declined as a result of reductions in U.S. steel production, recent increases in steel output have led to additional demand for shipping (The New York Times, 1988).

Great Lakes ships last over half a century and are designed to pass within a foot of the bottom of channels and locks. Cargo capacity is quite sensitive to lake and channel depth because of this low clearance. The presence of ice usually shuts down Great Lakes shipping up to 4 months each year.

Table 15-1. 1987 U.S. Great Lakes Shipping Cargo (thousands of tons)

Cargo	Weight	Percentage
Iron ore	61,670	36
Coal	37,731	22
Stone	33,164	19
Grain	22,338	13
Petroleum products	11,491	7
Cement	3,806	2
Potash	1,702	1
Total	171,902	100

Source: Nekvasil (Lake Carriers Association, 1988, personal communication).

Hydropower

The eight Great Lakes States use the connecting channels and the St. Lawrence River to obtain 35,435 gigawatt hours of hydropower each year, which is about 5% of their electricity generation. About four-fifths of the hydropower is produced in New York State, which derives over 26% of its electricity from hydropower (Edison Electric Institute, 1987).

Municipal Consumption

Most water used for the domestic and industrial consumption in the basin is taken from the lakes. Surface waters supply 95% of the basin's water needs. By the year 2000, consumption is estimated to increase by 50 to 96% (Ray et al., Volume J; Cohen, 1987b; IJC, 1985).

Fisheries

In 1984, the value of the harvest to the U.S. commercial fishing industry was approximately $15 million (U.S. EPA and Environment Canada, 1987; U.S. Department of Commerce, 1987). Although most fishing in the Great Lakes is for recreation, fisheries are managed by the states; the Great Lakes Fishery Commission coordinates activities among the states.

Tourism

Three national and 67 state parks are located along the shores of the lakes, as are numerous local parks. Over 63 million people visited these parks in 1983 (Ray et al., Volume J; Great Lakes Basin Commission, 1975). In 1984, lake-generated recreation yielded revenues of $8 to 15 million. Fishing, boating, and swimming are very popular.

Shoreline Development

Over 80% of the U.S. side of the Great Lakes shoreline is privately owned. One of the most developed shorelines is the 101-kilometer Illinois shoreline, where many parks and residential structures, including apartment houses, are built near the water's edge. Shoreline property owners have riparian rights to use adjoining waters. The shoreline property owners cannot substantially diminish the quantity or quality of surface waters (Ray et al., Volume J).

Climate and Water Quality

Water quality is directly affected by climate. Lower stream runoff increases concentrations of pollutants. Every summer, the lakes stratify into a warmer upper layer and a cooler lower layer. This stratification can limit biological activity by restricting the flow of nutrients between layers. In addition, warm temperatures and an excess supply of nutrients (phosphorous and other chemicals from agricultural runoff and sewage effluent) can lead to algal blooms that decay and cause a loss of oxygen (eutrophication) and reduction in aquatic life in the lower layers of lakes such as Lake Erie. Cool weather and the formation of ice help to deepen the mixed layer, break up the stratification, and thoroughly mix the lakes in the winter.

Development, industrialization, and intensive agriculture in the Great Lakes Basin have created serious pollution in the lakes, especially Lake Erie. In the early 1970s, nutrient loadings were so high that Lake Erie experienced significant eutrophication problems for several years (DiToro et al., 1987).

Two measures have helped improve water quality. The U.S.-Canada Great Lakes Water Quality Agreement of 1972 called for controlling nutrient inputs and eliminating the discharge of toxic chemicals, and the Clean Water Act mandated construction of sewage treatment plants and controls on industrial pollutants. The United States and Canada spent a total of $6.8 billion on sewage treatment in the Great Lakes. By 1980, nutrient loadings into Lake Erie had been cut in half (Ray et al., Volume J; DiToro et al., 1987), and water quality had markedly improved.

<u>Fluctuating Lake Levels</u>

Recent high and low lake levels have significantly affected users of the lakes. In 1964, Lake Michigan was 0.92 meters (3 feet) below average, making some docks and harbors unusable. Shipping loads were reduced by 5 to 10% and more shipments were required, subsequently raising the cost of raw materials and supplies by 10 to 15%. In addition, many water intakes had to be extended or lowered (Changnon, Volume H). Flow through the Niagara hydropower project fell by more than 20%, with electricity generation off by more than 35%. Flow through New York's St. Lawrence hydro project was more than 30% below its mean, with electricity generation decreased by 20% (Linder, 1987). However, low lake levels also provided benefits, for example, beaches became larger.

In the mid-1980s, a series of cool and wet years caused the lakes to rise to record heights. Apartment houses that were built too close to the shoreline during the low levels of the 1960s were flooded, as were roadways built close to the shore. The low water levels in the 1960s exposed the supporting structures along Chicago's shoreline to air, causing dry rot. When lake levels rose, the wood pilings and sections of the revetment collapsed. The estimated construction cost for rebuilding the damaged shoreline protection system is $843 million (Changnon, Volume H). The last 2 years have been relatively hot and dry, causing lake levels to recede to average levels. The lower levels have forced shippers to reduce tonnage just as the steel industry in the region is undergoing a resurgence.

Land Around the Lakes

The land in the Great Lakes region is extensively used for industry, agriculture, and forestry. Many of the uses are sensitive to climate.

<u>Land Uses</u>

Urban Development

Approximately 29 million people live in the Great Lakes Basin, mostly in the urban areas around the cities on the southern edge of the Great Lakes: Chicago, Detroit, Cleveland, Toledo, and Buffalo. Many of the residents work in manufacturing industries, which despite recent declines, still provide 23% of payroll employment (Ray et al., Volume J).

Agriculture

Agriculture is the single largest user of land: 42% of all land in the eight Great Lakes States is devoted to crops, and an additional 10% is used for pasture. The Great Lakes States encompass most of the Corn Belt. In 1983, roughly 59% of all U.S. cash receipts for corn and 40% of the receipts for soybeans came from this region. Overall, the Great Lakes States produced 26% of the total U.S. agricultural output, or $36 billion (Federal Reserve Bank of Chicago, 1985). Most crops are grown on dryland, as only about 1% of the region's croplands were irrigated in 1975 (U.S. Department of Commerce, 1987).

Livestock are also important to the agricultural economy of the region. Approximately 18% of U.S. cattle are raised in these eight states; of these, 52% are dairy cows (USDA, 1987). (The sensitivity of livestock to climate change is discussed in Chapter 6: Agriculture.)

Forests

The forests in the region have commercial, recreational, and conservation uses. The forests in the south are mainly oak and northern hardwoods, such as maple. The north has almost 21 million hectares (52 million acres) of forests consisting mostly of northern hardwoods, such as maple, birch, and beech, and boreal forests, such as spruce and fir trees. The federal and state governments own, respectively, 11 and 13% of the forests in Michigan, Minnesota, and Wisconsin, while over half are privately owned (USDA, 1982). The pulp, construction, and furniture industries are major consumers of such species as aspen, pines, balsam fir, spruce, maples, paper birch, and oak. The forest industry is a major employer in the northern part of the region. In Wisconsin, for example, 283,000 jobs are in timber harvesting and manufacturing related to forestry (Botkin et al., Volume D; U.S. EPA and Environment Canada, 1987). Forestry is considered to be a growth industry in the region, since Miclvgan has identified forest products as one of the three key industries targeted for expansion in the stale (Ray et al., Volume J).

PREVIOUS CLIMATE CHANGE STUDIES

The impacts of climate change on many of the systems in the Great Lakes have been analyzed in previous studies, mainly by Canadian researchers. These studies are summarized in Cohen and Allsopp (1988). Several Canadian studies have examined the potential impacts of climate change on Great Lakes levels and concluded that levels would fall. Southam and Dumont (1985) used the Goddard Institute for Space Studies (GISS) scenario to estimate that lake levels would fall by 0.2 to 0.6 meters (0.7 to 2 feet). Cohen (1986) used hydrologic calculations to estimate that the lakes might fall between 0.2 and 0.8 meters. More recently, Marchand et al. (1988) also used a hydrologic model of the lakes to estimate that the lakes would drop by an average of 0.2 to 0.6 meters. Cohen (1987a) found that changes in lake levels are very sensitive to humidity and windspeed. It is not known how climate change would affect these parameters on a regional scale. Wall (1985) concluded that lower lake levels could reduce ecological diversity and dry up enclosed marshes. In another study, Cohen (1987b) estimated that withdrawals of water from the lakes for municipal consumption would increase by about 2.5% on an annual basis and would only marginally affect lake levels.

Assel et al. (1985) studied the extent of ice cover during the winter of 1982-83, which had temperatures 3.3 to 4.4°C warmer than the 30-year mean. They found that ice cover on Lake Superior was reduced from a normal 75% coverage to 21%. On Lake Erie, ice coverage was down to 25% from the normal 90%. Meisner et al. (1987) conducted a literature review on the possible effects of global warming on Great Lakes fish. Results are discussed in the fisheries section of this chapter.

Marchand et al. (1988) (see also Sanderson, 1987) estimated the combined effects of lower lake levels and reduced ice cover due to climate change, and higher water consumption and shipping tonnage due to population and economic growth of Canadian shipping and hydropower production. They found that without economic changes, lower lake levels would increase shipping costs by 5%. After consideration of economic growth, lower lake levels and reduced ice cover could increase shipping costs by 12%.

Linder (1987) used the transient scenarios to estimate impacts on electricity demand and hydropower generation in 2015 in upstate New York. He found total energy demand declining by 0.21 to 0.27%, but peak demand increasing by 1 to 2%. Meanwhile, hydropower production could decline between 6 and 8.5% as a result of reductions in streamflow.

Impacts on managed and unmanaged vegetation have also been studied. The Land Evaluation Group examined the potential impacts of climate change on agriculture in Ontario and found that yields could decrease in southern Ontario and farming could become feasible in northern Ontario. The study also indicated that the direction of change for yields depends on whether rainfall increases or decreases (Land Evaluation Group, 1986). Solomon and West (1986) used a stand simulation model (see this chapter, Forests) to estimate the impacts of doubling and quadrupling of CO_2 levels on a northwest Michigan coniferous-deciduous transitional forest. They found that doubled CO_2 would lead to an eventual disappearance of boreal forests and an increase in deciduous trees. Total biomass would decline at first and rebound in about two centuries.

Two studies by Canadian researchers examined the possible impacts of climate change on tourism and recreation in Ontario. Both studies used climate change scenarios based on the GISS and Geophysical Fluid Dynamics Laboratory (GFDL) models (although these may have been earlier model runs). Crowe (1985) estimated that snowfall would decrease by 25 to 75%, and the ski season would be cut by 75 to 92% (7 to 12 weeks) in southern Ontario and by 13 to 31% (2 to 4 weeks) in northern Ontario. Wall found similar results. He concluded that reduced snowfall could eliminate skiing in southern Ontario and would shorten the northern Ontario ski season by 30 to 44%. A longer summer season could increase such summer tourism activities as camping. Wall (1985) also thought that lower lake levels could decrease ecological diversity and dry up enclosed marshes.

GREAT LAKES STUDIES IN THIS REPORT

Unlike previous studies, the studies for this report used common scenarios to address some of the potential impacts of climate change on a number of natural and societal systems in the Great Lakes region. The studies address the direct effects of climate change on the resources and some of the indirect effects on infrastructure and society. They focused on the lakes themselves, examining such issues as lake levels, ice cover, thermal structure, and fisheries. They also looked at the effects of these changes on shipping and shoreline properties, and examined the sensitivities of agriculture and forest to climate change. Finally, the studies examined the implications of climate change for Great Lakes policies and institutions. Some of the studies were linked quantitatively, but most were conducted independently of each other.

The studies involved either new topics or approaches that were not used in previous studies. For example, the analysis of lake levels used a more complex hydrologic model than was used previously. The agriculture analysis complements the Land Evaluation Group's study of Ontario by using a different model to examine impacts on the U.S. side of the lakes. The potential impacts of climate change on thermal structure were examined for the first time. Also for the first time, models were used to analyze impacts on fisheries. This study complements previous studies on forests by using a combination of modeling techniques to test the similarity of results.

The following analyses were performed for this report:

Direct Effects on Lakes

- <u>Effects of Climate Changes on the Laurentian Great Lakes Levels</u> - Croley and Hartmann, Great Lakes Environmental Research Laboratory (Volume A)

- <u>Impact of Global Warming on Great Lakes Ice Cycles</u> - Assel, Great Lakes Environmental Research Laboratory (Volume A)

<u>Impacts of Lake Changes on Infrastructure</u>

The results from the first two studies were used in the following studies:

- <u>Effect of Climatic Change on Shipping Within Lake Superior and Lake Erie</u> -Keith, DeAvila, and Willis, Engineering Computer Optecnomics, Inc. (Volume H)

- <u>Impacts of Extremes in Lake Michigan Levels Along Illinois Shoreline Part 1: Low Levels</u> - Changnon, Leffler, and Shealy, Illinois State Water Survey (Volume H)

Water Quality

The following studies focus on water quality and the effects on aquatic life in the lakes. The first two studies examined the direct effects of climate on the thermal structure of some of the lakes.

- <u>Potential Climatic Changes to the Lake Michigan Thermal Structure</u> - McCormick, Great Lakes Environmental Research Laboratory (Volume A)

- The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, Hydroqual, Inc. (Volume A)

The results from these studies were used in the following:

Potential Responses of Great Lakes Fishes and Their Habitat to Global Climate Warming - Magnuson, Regier, Hill, Holmes, Meisner, and Shuter, Universities of Wisconsin and Toronto (Volume E)

Forests

A series of studies on forests was commissioned to examine shifts in ranges, transient impacts, and the potential for migration of some Great Lakes forests. Basically, these are different analytic techniques for understanding how climate change may affect the composition and abundance of forests in the region.

- Transient Effects on Great Lakes Forests -Botkin, Nisbet, and Reynales, University of California at Santa Barbara (Volume D)

- Hard Times Ahead for Great Lakes Forests: A Climate Threshold Model Predicts Responses to CO_2 Induced Climate Change - Zabinski and Davis, University of Minnesota (Volume D)

- Assessing the Response of Vegetation to Future Climate Change: Ecological Response Surfaces and Paleoecological Model Validation - Overpeck and Bartlein, Lamont-Doherty (regional results were taken from this study) (Volume D)

Agriculture

The potential changes in agriculture in the Great Lakes were analyzed by studying changes in crop yields in the region and integrating the results in a national analysis of production changes. That national analysis was used to determine if production in the region could increase or decrease. The results of these studies were used to examine potential farm level adjustments.

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- Effect of Global Climate Chanye on Agriculture: Great Lakes Region - Ritchie, Baer, and Chou, Michigan State University (Volume C)

- Farm Level Adjustments by Illinois Corn Producers to Climatic Change - Easterling, Illinois State Water Survey (Volume C)

This chapter will use regional results from the following:

- The Economic Effects of Climate Chanee on U.S. Agriculture: A Preliminary Assessment - Adams, Glyer and McCarl, Oregon State University (Volume C)

Energy

This project analyzed potential changes in the national demand for electricity and estimated changes in regional demands. Results for the Great Lakes region are presented in this chapter.

- Electric Utilities - Linder and Inglis, ICF, Inc. (Volume H)

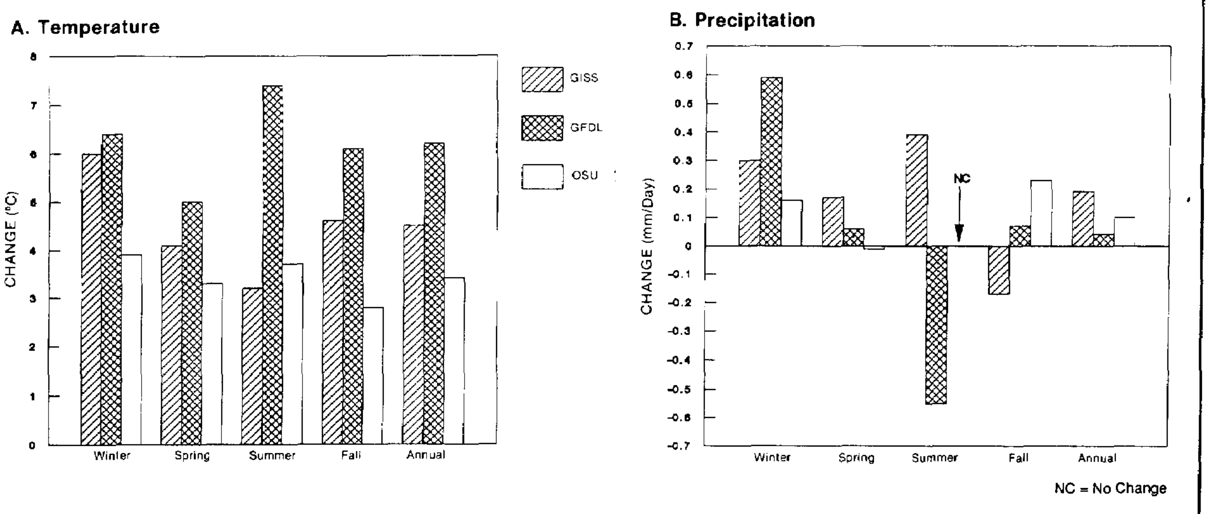
Policy

The potential policy implications of the changes indicated by these and previous studies for local, state, federal, and international decisionmaking are examined. This project provided information for the background and policy implications sections.

- Effects of Global Warming on the Great Lakes: The Implications for Policies and Institutions - Ray, Lindland, and Brah, The Center for the Great Lakes (Volume J)

GREAT LAKES REGIONAL CLIMATE CHANGE SCENARIOS

All three general circulation models (GCMs) that provide the basis for the climate change scenarios show rather large increases in temperature for the Great Lakes region under the doubled CO_2 climate. The seasonal and annual temperatures and precipitation are displayed in Figure 15-2. The Oregon State University (OSU) scenario has an annual temperature rise of 3.5°C, with no change in seasonal pattern. The Goddard Institute for Space Studies (GISS) scenario is about a degree warmer on average and has the largest warming in the winter and fall. The Geophysical Fluid Dynamics Laboratory (GFDL) scenario has the largest warming of the three models, about 6.5°C annually, with the largest warming in the summer. All three scenarios have annual increases in precipitation. OSU has an increase of approximately 0.1 millimeters per day (0.1 inches per year), with precipitation rising in all seasons. GISS has an increase of approximately 0.2 millimeters per day (0.03 inches per year), with precipitation declining slightly in the fall. GFDL has an annual precipitation increase of only 0.05 millimeters per day (0.07 inches per year), but rainfall drops by 0.5 millimeters per day (0.02 inches per day) in the summer. The large temperature increase and small rainfall increase combine to make GFDL the most severe scenario. This is especially true in summer months, when GFDL has the largest temperature rise of any scenario and is the only scenario that reduces rainfall. OSU is the mildest scenario owing to the smaller temperature increase. (Other runs of the GFDL model have lower temperature increases, although they still estimate a decline in summer rainfall.) GISS is in the middle in terms of severity, and OSU is the mildest of the three scenarios.



One limitation related to using the GCMs as a basis for climate change scenarios for the Great Lakes region is that the lakes are not well represented in the GCMs. The relatively large size of the GCM grid boxes results in little feedback from the lakes to the regional climate estimates from the GCMs.

RESULTS FROM THE GREAT LAKES STUDIES

Lakes

Lake Levels

Geologic records indicate that Great Lakes levels have fluctuated as paleohistoric climates have been wetter and drier (Larson, 1985). Recent shortterm variations have been the result of short-term changes in precipitation patterns. Croley and Hartmann examined the potential impacts of global warming on average lake levels.

Figure 15-2. Average change in temperature (A) and precipitation (B) over Great Lakes gridpoints in GISS, GFDL, and OSU models ($2xCO_2$ minus $1xCO_2$).

Study Design

Croley and Hartmann used a water supply and lake level model of the Great Lakes Basin developed by the Great Lakes Environmental Research Laboratory to estimate the potential impacts of climate change on levels of the Great Lakes (Croley, 1983a,b; Croley, 1988; Quinn, 1978). This model is the most detailed hydrologic model of the Great Lakes Basin and includes a separate model for each of the 121 watersheds in the basin. Croley and Hartmann simulated runoff in each of the subbasins, overlake precipitation, and evaporation.[2] Lake levels are very sensitive to evaporation; therefore, Croley and Hartmann ran each GCM scenario with different assumptions about evaporation. Finally, they used the current plans (Plan 1977 for Superior and Plan 1958-D for Ontario) and hydraulic routing models of outlet and connecting channel flow and estimated water levels on each of the Great Lakes.

The regulation plan for Lake Superior failed under the GFDL scenario. To obtain an estimate of changes in levels for Superior-Huron, St. Clair, and Erie, Croley and Hartmann assumed that over a 30-year period, total inflows into Lake Superior (runoff + overlake precipitation + diversions -evaporation) would equal total outflows, and Lake Superior levels would not change. No figures are presented for changes in the level of Lake Superior in the GFDL scenario. The levels of Lake Superior would probably fall. Only 30-year average lake levels were calculated for the other lakes.

Limitations

The relationships in this model were developed for a cool and wet climate. The analysis did not account for changes in the consumptive uses of the lakes (due to population and economic growth or climate change), and it did not consider changes in the regulation plans, or increases in or additions to diversions into or out of the lakes. The analysis also used the difference in vector winds from the GCMs as a proxy for the difference in scalar winds because GCM estimates of changes of scalar winds were not available. Thus, the wind estimates probably underestimate changes in windspeed (David Rind, Goddard Institute for Space Studies, 1988, personal communication). The uncertainty on winds is complicated by the uncertainties concerning evaporation. Different assumptions of evaporation in this analysis affect the magnitude of lake level drop, but they do not affect the direction of change -- lake levels fall under all evaporation assumptions. Cohen (1987a) found that potential changes in Great Lakes levels are very sensitive to estimates of changes in windspeed and humidity. He concluded that with the right combination of conditions, even with higher temperatures, it is possible for lake levels to rise.

Results

Lake levels were estimated to fall significantly under all three scenarios (see Table 15-2). The lake level changes are displayed in ranges from low to high evaporation.

Average levels for Lake Superior would be about 0.4 to 0.5 meters (1.3 to 1.7 feet) below average levels for the 1951-80 period under the OSU and GISS scenarios. These average levels would be generally lower than recorded lows of recent history. The lakes would likely still fluctuate around these average levels, so levels during some years would be lower. Even though precipitation rose in all three scenarios, lake levels were estimated to fall, primarily as a result of the higher temperatures. Apparently, only a large increase in rainfall or humidity or a large decrease in windspeeds could offset these changes. Lake levels were estimated to continue fluctuating on an annual basis. Specific

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[2] In Volume A, Croley focuses on results from his latest run. This run includes assumptions that lead to relatively high amounts of evaporation and larger drops in lake levels. Earlier runs had less evaporation and larger drops in lake levels. Results in this chapter include the latest run and an earlier run.

estimates of fluctuation are not discussed here, since variability was assumed not to change.

Croley and Hartmann also found that the flow in the St. Mary's could increase by less than 1% in the GISS high rainfall scenario and drop by 13% in the drier OSU scenario for Lake Superior. The flow in the Niagara River was estimated to be 2 to 30% lower. Croley and Hartmann did not estimate the flow of these rivers for the GFDL scenario.

The lowering of lake levels appears to be correlated with increased temperatures in the scenarios. Under all the doubled CO_2 scenarios, there could be declines in runoff to the lakes and increases in evaporation from the lakes. The reduction in runoff would be largely the result of changes in snowpack accumulation and ablation. Snowpack in the Lake Superior Basin could be reduced by one-third to two-thirds, and in the other basins, farther to the soutl4 the snowpack could be almost entirely absent. The reduction in runoff would reduce average streamflow in the basin. These results appear to be driven mainly by the temperature increase, since precipitation rises in all scenarios.

Table 15-2. Doubled CO_2 Scenarios: Reduction in Average Great Lakes Levels from 1951 to 1980 (meters).

Scenario	Superior	Michigan	Erie	Ontario
GISS	-0.43 to -0.47	-1.25 to -1.31	-0.95 to -1.16	NA
GFDL	NA	-2.48 to -2.52	-1.65 to -1.91	NA
OSU	-0.39 to -0.47	-0.86 to -0.99	-0.63 to -0.80	NA
Transient Scenario (average rate of change per decade 1980-2060)				
GISS-A	-0.006	-0.055	-0.04	NA

NA = Not applicable
Source: Croley and Hartmann (Volume A).

Evaporation would increase under all three scenarios. The increase in evaporation varied under different assumptions about the relationship of evaporation to change in climate variables and ranged from 20 to 48%. For a given assumption about evaporation, higher temperature scenarios would generally cause more evaporation. Lake level reductions could also be higher or lower, depending on these assumptions.

All of these changes could cause a reduction in net basin supply (the sum of overlake precipitation and runoff minus evaporation) by 14 to 68%. The exception to this is the GISS scenario for Lake Superior. In that scenario, annual rainfall increased by 18%, which could lead to a 1% increase in net basin supply.

The Ontario regulation plan would fail under all scenarios, including the transient run. Under these conditions, the system would not contain enough water to keep the level of Lake Ontario and the flow in the St. Lawrence River within ranges currently specified by the plan. The Lake Superior regulation plan was estimated to fail under the GFDL scenario. Although net basin supply in Lake Superior increased under GISS, the regulation plan would require increased flow through the St. Mary's River to the water-short lower lakes, resulting in a net drop in Lake Superior levels.

These results are consistent with other studies done on lake levels and climate change. Both Cohen and Sanderson agree with Croley and Hartmann that lake levels would drop under various climate change scenarios. The other two studies, however, estimated lake levels would drop less than 1 meter. Croley and Hartmann may have estimated greater changes because they used a more sophisticated runoff, evaporation, and routing model and because of different assumptions made about evaporation. Croley and Hartmann also used a more integrated approach and more variables from the GCMs. The estimates for GFDL may also be higher because the GFDL scenario used in this study had a higher temperature rise than the GFDL scenarios used by Cohen and Sanderson.

The results of the transient run (GISS A) are expressed as the average change in lake level per decade and are not indicative of what would happen in any particular decade. Lake Superior levels drop only 0.006 meters (0.2 inches) per decade, while the other lake levels fall 0.04 to 0.055 meter (1.6 to 2.2 inches) per decade. An extrapolation of the transient results to the decade of the 2060s (when the GISS A transient run reaches doubled CO_2 climate conditions) results in lake level reductions less than for the doubled CO_2 GISS scenario. This is because lake levels may not respond immediately to climate change, but must catch up. The results may also be affected by the variability assumptions in the transient scenarios (see Chapter 4: Methodology). By the end of the transient scenario, the 2050s, lake levels fall at a faster rate -- by more than 0.05 meters (2.0 inches) per decade. Thus, these studies do not clearly indicate the length of time required for the lakes to drop by the amounts shown in Table 15-2.

Croley and Hartmann found that enough heat could reside in Lakes Superior, Michigan, Huron, and Ontario to maintain water surface temperatures at a sufficiently high level throughout the year, so that buoyancy-driven turnovers of the water column may not occur at all. This could significantly affect lakewater quality and aquatic life (see this chapter, Thermal Structure of Southern Lake Michigan). Croley estimated that average surface water temperatures in the winter would be above 0°C and would significantly reduce ice concentrations.

Implications

Hydropower production could be reduced, as flows through the St. Mary's, the Niagara, and the St. Lawrence Rivers fall. Losses to hydropower were not estimated for the EPA study, although Linder's earlier work on hydropower losses by 2015 in New York State showed potential loss of 1500 to 2066 gigawatt-hours (6 to 9%) (Linden, 1987). Sanderson (1987) estimated that under a doubled CO z scenario, Canadian hydroelectric power production on the St. Mary's River could rise by 2.5% (because the level of Lakes Michigan-Huron falls more than that of Lake Superior) and power production on the Niagara River could fall by 13 to 18% as a result of a drop in flow. The impacts of lower lake levels on wetlands were not estimated, and the impacts on shipping and on shoreline infrastructure are discussed later in this chapter.

Lower lake levels and reduced riverflow would likely adversely affect water quality in the basin. Less water would reduce dilution of pollutants. Forty-two "hot spots" occupy many bays and harbors along the Great Lakes. These are contaminated with a wide variety of halogenated organics and heavy metals, as well as remobilizable nutrients. Lower lakes may cause emergence and near emergence of these toxic sediments through erosion, leaching, oxidization, or volatilization.

Higher temperatures may lead to increased withdrawals of water from lakes for municipal consumption. Climate change may also result in more calls for diversion of water out of the Great Lakes Basin for use elsewhere. However, lake levels may be lowered even more as a result of higher demand for withdrawals for use in the basin as a result of population and economic growth.

Effects of Lower Lake Levels

Coastal infrastructure around the Great Lakes has generally been built assuming average lake levels would not change. A drop in levels could make much of the current infrastructure unusable and necessitate reconstruction. Changnon et al. examined the potential impacts and adjustments to infrastructure along the 101-kilometer (63-mile) Illinois shoreline. This study and the shipping analysis used the lower range of the lake level drops from Table 15-2 because subsequent analyses that gave different lake levels were performed too late to be incorporated.

Study Design

Changnon et al. interviewed experts about the possible impacts and costs of adjustment along the Illinois shoreline to the lower lake level estimates described above. Results are expressed in current dollars.

Limitations

This analysis did not use economic models, used current prices, and did not consider changes in population, GNP, or technology. Results are based on expert judgment. Changnon et al. also assumed that lakes would reach the levels described above by 2030. The change in lake levels may not be reached until decades later (by the year 2060 or later) so costs may be borne over a longer period than Changnon estimated, allowing for more routine replacement of infrastructure. This study examined only the costs of rebuilding infrastructure and did not examine ecological impacts.

Results

The largest costs appear to accrue to recreational and commercial harbors (see Table 153). The major expenses are associated with dredging harbors and lowering bulkheads, which could cost approximately $200 to $400 million. If lake levels fall enough, keeping some harbors open (e.g., Waukegan, Illinois) may not be a cost-effective choice.

Changnon et al. concluded that slips and docks would be only slightly affected. Many of these probably would have been replaced anyway and could be set at lower levels as the lakes fall. (The impacts on commercial shipping in Lakes Superior and Erie are discussed below.)

Intake valves for municipal and industrial consumption could be exposed and may have to be lowered or moved farther offshore. Outfalls for stormwater would have to be extended. Changnon et al. estimated that extending urban water intakes and stormwater outfalls could cost $16 to 17 million.

Although the exposure of more land could present some erosion problems, it could also enlarge many beaches. An additional 1 to 2.2 square kilometers (0.3 to 0.8 square miles) of beaches would be added to the Illinois shoreline. In all, Changnon et al. estimated that the costs of adjusting to lower levels of 1.25 to 2.5 meters along the Illinois shoreline, excluding normal replacement of docks and piers, would be $220 to $430 million. If normal replacement costs do not account for lower lake levels, costs could be $30 to $110 million higher. To put these figures into context, the City of Chicago may spend over $800 million to repair shorelines damaged by high water levels in recent years.

Walker et al. (Volume H; for a discussion of methodology and results, see Chapter 13: Urban Infrastructure) examined the potential capacity of climate change on Cleveland's infrastructure. They found that savings in such areas as snow removal and bridge repair could offset increased cooling and dredging costs. Cities on the Illinois shoreline would also have savings due to reduced winter expenditure.

Table 15-3. Estimated Economic Impacts of Lowerings of the Levels of Lake Michigan Over a 50-Year Period (1990-2040)

Types of Expenses	Cost[a]	
	1.25 meters lower	2.5 meters lower
Recreational harbors	30-50	75-100
Dredging	15	35
Sheeting	20[b]	40[b]
Slips/docks		
Commercial harbors		
Dredging	108	212
Sheeting	38	38
Slips/docks	40[b]	90[b]
Water supply sources		
Extending urban intakes	15	15
Wilmette Harbor Intake	1	2
Beaches		
Facility relocations	1-2	1-2
Outfalls for stormwater		
Extensions and modifications	2	4
Total	$270-292[b]	$512-540

[a] Costs in millions of 1988 dollars to address future lake levels at indicated depths below average (1951-80) levels of Lake Michigan.

[b] Some costs could be partly covered by normal replacement expenditures over the period of changing levels.
Source: Changnon et al. (Volume H).

Ice Cover

Warmer winters would reduce ice cover on the Great Lakes. Some analysts have speculated that ice would be completely eliminated. Assel used a model to estimate the potential extent and duration of ice cover.

Study Design

Assel developed a statistical relationship between temperature and ice cover for this study. The models were developed for the three basins of Lake Erie, for the Lake Superior Western and Eastern Basins, and for Whitefish Bay in Lake Superior. Whitefish Bay was included because it has the longest period of ice cover and acts as a choke point on shipping in and out of Lake Superior. Lakes Superior and Erie represent extremes in terms of air temperature regimes, lake depth, and heat storage capacity, and bound the range of potential ice cover changes.

Limitations

Assel's study did not consider the effects of wind and other variables on ice formation. Implicitly, the analysis assumed that winds stay the same. Stronger winds would make the ice season shorter than estimated, and weaker winds (and calmer waters) would make it longer. The three GCMs estimate that windspeeds over the two lakes drop by 0.0 to 0.3 meters per second (see Croley, Volume A). Inclusion of windspeed changes would have lowered ice cover reduction results. The model was built based on the relatively cool years of the 1960s and 1970s; therefore, the doubled CO_2 scenario temperatures are outside the range of winter temperatures in those years. However, the model simulated ice duration within 3 weeks of actual ice duration for the warm winter of 1982-83.

Results

Assel found that although average ice cover might be significantly reduced, ice would still form on the lakes (Table 15-4). Results for the central basin of Lake Erie are displayed in Figure 15-3. It now averages 83 days of ice cover. In the 1981-2009 transient scenario, ice cover was estimated to be 71 days; in the 2010-2039 scenario, it was estimated to decline to 41 days. Under the doubled CO_2 climate, ice cover could be reduced to a total of 6 to 19 days, and ice formations would be generally limited to near-shore and shallow areas. Whitefish Bay in Lake Superior currently averages about 115 days of ice cover. Under the doubled CO scenarios, ice duration would be reduced to 69 to 86 days. Also, the maximum percentage of Whitefish Bay covered by ice would be reduced from close to 100% to 70-20%.

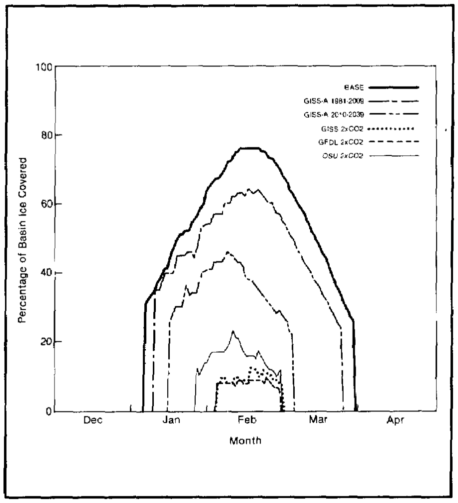

Figure 15-3. Changes in duration and extent of ice cover in central basin of Lake Erie under transient and doubled CO_2 scenarios (Assel, Volume A).

The temperature rise in the scenarios may not be warm enough to eliminate ice cover on the Great Lakes, but many winters could have no ice at all. The Lake Erie Central Basin is estimated to be ice-free from 11 to 22 years out of 30 years, rather than 1 out of 30 years, as estimated for base climate conditions. This result appears to be sensitive to depth, as estimates indicate that the deeper Lake Erie East Basin would be ice-free 60 to 84% of the time, and the shallow West Basin would be ice-free in 7 to 17% of the winters. Since it is colder, Lake Superior would have ice cover in virtually all winters under the scenarios.

Assel found that ice cover reductions during the first 30 years of the transient scenario (model years 1981-2010) may not be significantly different than under current conditions. The length and extent of ice cover noticeably decline, beginning in the second 30 years of the transient scenario (201140). By the last decade of the transient scenario, the 2050s, the extent of ice cover was almost identical to the GISS doubled CO_2 coverage.

Table 15-4. Reduction in Ice Cover in Lakes Erie and Superior (average annual days of cover)

Lake	Base	GISS Transient A		Doubled $_{CO2}$			Analog
	1951-80	1981-2009	2010-2039	GISS	GFDL	OSU	1930s
Erie West	93	84	54	26	23	35	85
Erie Cent	83	71	41	8	6	19	61
Erie East	97	82	43	6	5	13	70
Supr West	112	108	88	46	24	75	106
Supr East	108	103	84	43	19	69	103
Supr WFB	115	109	92	55	26	80	112

Abbreviations:
Supr = Superior; WFB = Whitefish Bay; Cent = Central.
Source: Assel (Volume A).

Croley also found that ice cover would be reduced. His analysis found that average surface temperatures on all the lakes in the winter could be above 0°C. Even if average temperatures are that high, water temperatures in near-shore and shallow areas, the areas to which Assel said ice would be limited, would be sufficiently cold to cause ice formation.

Implications

Ice cover reductions could have positive and negative effects. On the positive side, the shipping season would be extended (see below). Water would flow more freely through rivers and connecting channels, allowing for more hydropower production in the winter. On the other hand, ice protects some aquatic life, such as whitefish, and protects shorelines against the erosive impact of high-energy waves (Meisner et al., 1987).

Shipping

With lower lake levels, ships would have to reduce their cargo, or ports and channels would have to be dredged. However, the shorter duration of ice cover would allow for a longer shipping season. The additional days of transport may make up for the loss of capacity on each voyage.

Study Design

Keith et al. studied the potential impacts of changes in lake levels and ice cover on shipping in six ports: Two Harbors; Duluth/Superior and Whitefish Bays in Lake Superior; and Toledo, Cleveland, and Buffalo in Lake Erie. They used the "ECO Great Lakes Shipping Model," which includes current data on major ports and commercial ships in the Great Lakes, types of cargo, costs of transport, and operating costs. Keith et al. used lake level reductions from Croley and Hartmann to study the change in cargo capacity and costs per ton, and they used the change in cargo capacity to estimate how many days of shipping would be needed to transport the same amount of cargo as transported at present. The latter figure was compared to ice duration reductions estimated by Assel to determine whether the shipping season was sufficiently extended to allow for transport of the same amount of annual cargo as currently transported.

Limitations

The analysis did not consider changes in the composition of the fleet or in the mix and amount of cargo. It also assumed that demand for shipping of goods did not change, even in response to changes in availability of shipping. The analysis did not examine whether goods would shift to or from alternate ports or means of transportation and how changes in the costs of shipping and in the shipping season would affect users. Keith et al. also assumed that channels were not dredged to be deeper. Thus, analysis is useful for estimating the direction and approximate magnitude of change, but quantitative results should be interpreted with caution.

Results

The costs of shipping were estimated to increase as a result of lower lake levels. The effect on the cargo load for ships using the Port of Buffalo are displayed in Figure 15-4. Under drops of 0.7 to 1.0

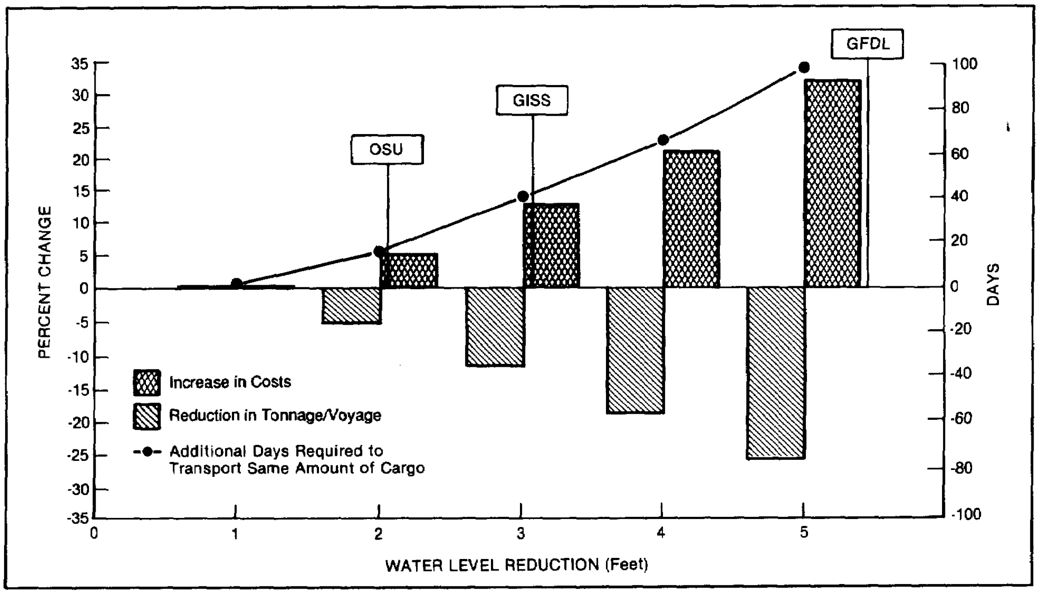

Figure 15-4. Impacts of lower lake levels and reduced ice cover on shipping, cargo capacity, costs, and days of transport for the Port of Buffalo (Keith et al., Volume H).

meter in Lake Erie, which are the lake level reductions estimated by Croley for the OSU and GISS scenarios, cargo capacity would decrease by about 5 to 13%, and costs per ton would rise by the same amount. Croley's estimate from the GFDL scenario was that Lake Erie would fall 1.65 meters (5.4 feet), but the shipping model does not include lake level drops of more than 5 feet. A drop of 5 feet would decrease cargo capacity per voyage by 27% and increase costs by 33%. Thus, the drop in lake levels estimated under the GFDL scenario could increase costs by more than 33%. Since lake levels in Lake Superior were not estimated to fall as much, the corresponding reduction in cargo capacity for ships on those ports would be in the range of 2 to 8%.

Sanderson estimated that lake level reduction of 0.2 to 0.6 meters would increase total Canadian shipping costs by 5%, assuming the current fleet and mix stayed the same. Although results are not directly comparable, since Keith et al. examined U.S. flagships and ports while Sanderson studied Canadian ships and ports, the estimates are of the same magnitude.

Whether the same amount of annual cargo can be transported, assuming no dredging to deepen channels, depends mostly on how much lake levels drop. If the drop is sufficiently large, annual tonnage could be reduced. The following discussion assumes that lake level declines occur at the same time as ice cover reductions. It is not clear from these studies whether lake levels will respond more slowly to climate change than ice cover. Figure 154 also displays the additional days needed to transport the same amount of cargo as is currently shipped through Buffalo. Under the approximate 2-to 3-foot drop of the wetter and relatively cooler OSU and GISS scenarios, another 15 to 40 days of shipping would be needed. Assel estimated that under those scenarios, ice duration in eastern Lake Erie would be reduced by 84 to 91 days. Thus, under these scenarios, even with reduced capacity per voyage, there would be enough additional days of travel to transport even more goods. If lake levels fell 5 feet, which is less than estimated by GFDL, an additional 100 days of transport would be needed to handle the same amount of cargo. Ice duration in eastern Lake Erie could be reduced by 92 days under this scenario, which would not allow enough time to transport the same amount of cargo, assuming the current fleet and demand for transport. The results appear to be more sensitive to changes in lake levels than to reductions in ice cover.

Keith and Willis used current dredging costs to estimate the cost of dredging the ports to restore current channel depths. The total costs of dredging the three ports in Lake Erie range from $7 to $31 million per port (1987 dollars). Current annual dredging costs for those ports range from $800,000 per year in Buffalo to $2.5 million per year in Toledo (J. Hasseler, U.S. Army Corps of Engineers Buffalo District, 1988, personal communication).

Implications

Reduction in the tonnage per voyage or increased costs for dredging would raise shipping costs. However, with a longer shipping season, users of shipping such as powerplants would not have to carry large inventories to last through the winter and own enough land to store those inventories. Besides reducing costs, this could allow current lakefront storage areas to be used for other purposes. Whether these savings would offset higher shipping costs was not examined.

Dredging the ports and channels could degrade the water quality of the lakes. The sediments in many of these ports are toxic, and disposal of the sediments could be complicated by their toxicity and by the reduced disposal areas resulting from lower lake levels.

Water Quality

Two studies estimated the temperatures and thermal structures of southern Lake Michigan and the Lake Erie Central Basin. The Lake Erie study estimated biological activity, such as algal production and changes in dissolved oxygen levels. The Michigan and Erie analyses were used by Magnuson et al. to study changes in the thermal habitats of fish.

Thermal Structure of Southern Lake Michigan

Study Design

McCormick used a one-dimensional thermal structure model (Garwood, 1977) to estimate the heat content and structure of a site in south-central Lake Michigan. The model has been successfully applied to oceans and inland seas and was used by McCormick to analyze a site 150 meters (500 feet) deep. GCM data for windspeed, temperature, humidity, solar radiation, and cloud cover were applied to hourly data from 1981 to 1984.

Limitations

McCormick used the years 1981-84 as his base case because hourly water temperature data are not available for 1951-80. Three years provide very limited baseline climate variability, although these years include cold and warm periods. The results are most sensitive to changes in windspeed. Since the scenario may underestimate reductions in windspeed from the GCMs (see the discussion of the limitations of the lake level study), this analysis may overestimate wind-driven mixing in the upper layer and underestimate changes in the length of time and degree of stratification. On the other hand, if the intensity of summer storm increases, then stratification may be weakened and shortened. The analysis assumed there was no change in the frequency of storms. More summer storms may weaken stratification, while fewer storms could strengthen stratification.

Results

McCormick estimated that the length of the stratified season could increase under all three scenarios. Figure 15-5 displays the mixed-layer depth over an average year. The higher heat content may cause the lake to begin to thermally stratify, on average, about 2 months earlier than in the base case (in April as opposed to June). The stratified layers were estimated to begin to deepen around late fall, as under current climate conditions.

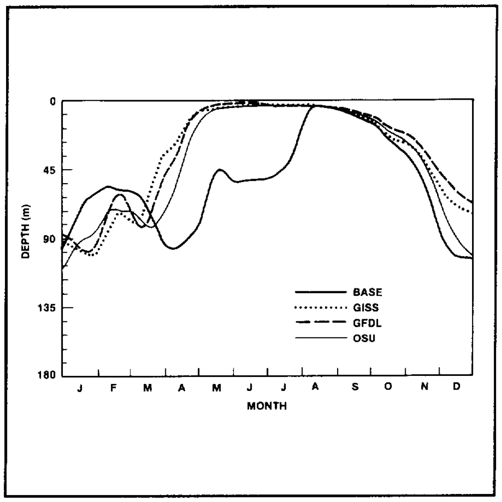

Figure 15-5. Average annual mixed-layer depth in southern Lake Michigan (McCormick, Volume A).

Surface lake temperatures were estimated to be up to several degrees higher than in the base case. The increase in surface temperatures was greater than the increase in subsurface temperatures. There appears to be a larger warming of the entire water column in the winter, about 2 to 3°C, than in the summer, which has a warming of about 2°C. The warmer lake temperatures are consistent with the studies of Croley and Assel, which suggest that midlake water would generally be ice-free. The earlier onset of stratification, reduced inds in the scenarios, and greater temperature differences between lake layers could yield stronger density differences between upper and lower layers.

McCormick detected a significant decrease in the frequency of complete mixing of the lakes. The surface layer could be warmer and more buoyant, making it more difficult for entrainment and mixing to occur. Temperatures were too warm in the winters of some years to allow the lake to become isothermal (the mixed layer would stay above the bottom of the lake all year), leading to a year-long stratification. This result is consistent with Croley's analysis.

Implications

Reduced turnover of the lakes could have serious implications for aquatic species in the lakes. Mixing of oxygen and nutrients could be disrupted, possibly affecting the abundance of life in the lower and upper layers of the lakes.

Eutrophication of the Lake Erie Central Basin

Nutrient loadings have made many areas of the shallow Lake Erie eutrophic at times. The shallow western and central basins of the lake are particularly vulnerable to eutrophication. Installation of pollution controls in recent years has improved water quality. Blumberg and DiToro analyzed whether climate change would have an effect on eutrophication in the Lake Erie Central Basin.

Study Design

Blumberg and DiToro modeled the thermal structure of the Lake Erie Central Basin. They developed a thermal model for the basin, using a modeling framework previously designed by Blumberg (Blumberg and Mellor, 1983). This model is similar to the one used by McCormick for southern Lake Michigan.

Blumberg and DiToro then examined the direct effects of changes in the thermal structure on aquatic life in the basin. The outputs from the thermal model were fed into a eutrophication model that had been previously developed by DiToro (DiToro and Connolly, 1980). The latter model estimates what would happen to dissolved oxygen levels in the lakes by simulating the interactions between nutrient availability and biological (e.g., plankton) activity.

The models were run using only two base years, 1970 and 1975. In 1970, the thermocline (density gradient between the upper and lower layers) was deep, and over 60% of the hypolimnion (lower level) in the Lake Erie Central Basin was anoxic (depleted of oxygen). In 1975, the thermocline was shallow, and less than 10% of the lower layer was anoxic (DiToro et al., 1987).

Limitations

Although the two base years encompass a wide range of baseline anoxic conditions, they do not represent a full range of climate variability. In addition, as in the Lake Michigan study, the scenario assumed no change in the frequency of storms. More summer storms would weaken stratification and increase dissolved oxygen levels, while fewer storms would have the opposite effect. The analysis did not incorporate the actual reduction in nutrient loadings from the base years, or the estimated drop in lake levels from Croley's work. Lower lake levels would reduce the volume of the lower layer in Lake Erie, possibly increasing eutrophication. The models were not run for the winter, but Blumberg and DiToro tested the sensitivity of results to higher water column temperatures (due to warmer winter air temperatures) in the spring and found no significant difference in results. Blumberg and DiToro used the vector wind estimates from the GCMs, which may overestimate mixing in the upper layer.

Pollution loadings in 1970 and 1975 were much higher than they are today. Use of current pollution loadings would have resulted in higher estimates of dissolved oxygen levels and lower estimates of the area of the basin that could become anoxic. The direction of change estimated by Blumberg and DiToro would not have been affected.

Results

Blumberg and DiToro estimated that the Lake Erie Central Basin could remain stratified about 2 to 4 months longer than under current conditions, with the stratified season starting 2 to 6 weeks sooner and ending 2 to 7 weeks later. The temperature differences between the upper and lower layers of the basin were estimated to be greater under all scenarios, leading to less exchange of nutrients across the thermocline. The depth of the thermocline appears to be most sensitive to estimated changes in windspeeds. In two scenarios, GISS and GFDL, windspeeds were generally lower, and the thermocline was estimated to be about 2 meters higher than current depths. Under the OSU scenario, windspeeds were estimated to increase and the thermocline was estimated to be approximately 1 meter deeper than current levels. A lowering of the thermocline depth by 2 meters in the 25-meterdeep Lake Erie Central Basin can reduce the volume of the lower layer by 20%, limiting total oxygen availability.

All three scenarios generally led to decreases in dissolved oxygen levels compared with base case conditions despite differences in thermocline depth. The increase in area of the Lake Erie Central Basin that was estimated to become anoxic is shown in Figure 15-6. Dissolved oxygen levels were estimated to increase only in the July 1970 case, and this occurred because the levels were near zero to begin with. Blumberg and DiToro concluded that the difference in oxygen content was caused by warmer lake temperatures, which raise biological activity enough to increase oxygen demand.

The enhanced biological activity was combined with a more intense and longer stratified season to further lower dissolved oxygen levels. Lower thermocline depths, such as in the OSU scenario, result in even greater decreases in dissolved oxygen levels. The estimated changes in the thermal structure of Lake Erie are comparable to McCormick's results for southern Lake Michigan. Both estimated that average temperatures in the water column would rise, that there would be greater differences in temperature between the epilimnion and hypolimnion, and that stratification would last longer. One major difference in the results is that stratification begins earlier and lasts longer in Lake Erie and begins earlier and breaks up at the same time as the present stratification in Lake Michigan. It is not clear whether this difference is attributable to different lake depths, to surface meteorology used to force the models, or to surface boundary conditions in the calculations.

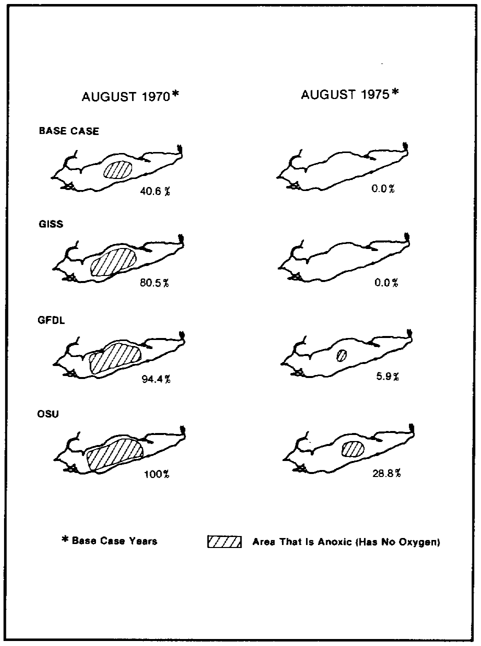

Figure 15-6. Area of central basin of Lake Erie that becomes anoxic (Blumber and DiToro, Volume A).

Implications

Decreased dissolved oxygen levels could make the Lake Erie Central Basin less habitable for finfish and shellfish during the summer. This could reduce recreational uses of the lake such as swimming, fishing, and boating. It also could put more pressure on reducing sources of pollutants, especially such nutrients as phosphorous, from point and nonpoint sources.

Fisheries

The Blumberg and McCormick studies show that climate change would probably raise lake temperatures and reduce oxygen levels in certain areas. To get an initial sense of what these changes might mean for Great Lakes fish, Magnuson et al. examined the potential ecosystem, organism, and population responses to warmer temperatures.

Study Design

Magnuson et al. estimated changes in fish habitat, growth, prey consumption, and population for sites in Lakes Erie, Michigan, and Superior. The work used several approaches and models to examine the following:

- Changes in ecosystem activity, such as changes in phytoplankton populations, were estimated by using a community "Q_{10}" rule (Ruttner, 1931), which approximates the higher biological activity associated with higher temperatures.

- Magnuson et al. used the Blumberg and McCormick thermal structure studies to estimate the potential effects on thermal habitats -- the niche in which temperatures are optimum for fish. To estimate changes in habitats, the study used laboratory estimates of the temperature regimes preferred by fish (Magnuson et al., 1979; Crowder and Magnuson, 1983) and assumed that the lower layer of the Lake Erie Central Basin is uninhabitable. In addition, using a thermal model for streams (Delay and Seaders, 1966), the study calculated the change in habitat for brook trout in a southern Ontario river.

- Magnuson et al. used a food consumption and conversion model (Kitchell et al., 1977) to estimate the changes in annual growth and prey consumption at three near-shore sites in Lakes Superior, Michigan, and Erie. This analysis assumed that consumption rates increase with climate warming. Growth simulation for Lake Michigan using water temperature scenarios from McCormick assumed that prey availability did not increase. This study assumed that fish migrate to habitable sites when inshore temperatures are too warm.

Limitations

The study did not examine the combined effects of reduced habitat and greater need for forage in the summer, which would combine to intensify species interactions. The analysis did not incorporate impacts resulting from lower lake levels, such as possible loss of wetlands, and it did not analyze the aquatic effects of the potential reduction in the frequency of lake turnover or the impacts of a reduction in ice cover. The introduction of new species, which could have negative impacts on existing fish, was not examined.

Any uncertainties associated with the McCormick and Blumberg studies would be carried over into the analysis on habitat. These changes in the lakes and littoral systems may have negative impacts on Great Lakes fish. These uncertainties could reverse the direction of results and lead to more declines in fish populations than indicated here.

Results

Phytoplankton production, zooplankton biomass, and maximum fishery yields were estimated to increase 1.3- to 2.7-fold, with the largest increase in phytoplankton production (1.6to 2.7-fold) (Figure 15-7). The larger increases in biological activity were generally associated with larger temperature increases. The increase in phytoplankton provides more forage for zooplankton, which, in turn, provides more forage for fish. The increase in phytoplankton can also enhance eutroplucation, as was estimated by Blumberg and DiToro.

Magnuson et al. found that the average annual thermal habitat for all fishes would increase. This was especially apparent for lake trout, which is a coldwater fish with a preference for very cold water, and which could have more than a 100% increase in habitat (see Figure 15-8). The major reason for the increase in habitat is that more habitable waters would be found in the fall, winter, and spring. On the other hand, hotter temperatures could decrease summer habitats for certain species by 2 to 47%, depending on the temperature rise and species. The length of stream suitable for brook trout in the summer could be reduced by 25 to 33% because of higher temperatures.

Fishes were generally estimated to have increased body size under the scenarios. Cool and cold coldwater fishes could have 20 to 70% more growth, and warmwater fishes in warm areas could have 220 to 470% more growth. This assumes that prey availability increases. If prey availability does not increase, fish growth would also decrease owing to an inability to compensate for the increased metabolic costs of living in higher temperatures. Magnuson et al. calculated that if prey availability does not increase, fish growth in Lake Michigan could decrease by 10 to 30%. Warmwater fish would have larger decreases if prey did not increase. Furthermore, the increased demand for forage may intensify species' interactions and alter the food web structure.

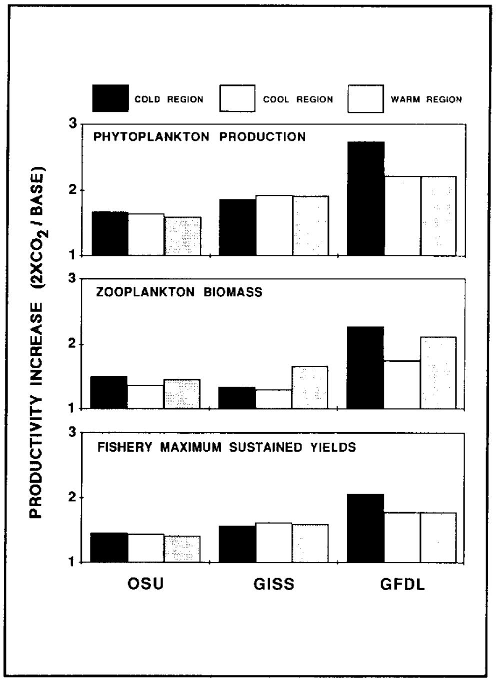

Figure 15-7. Increases in Great Lakes aquatic productivity (Magnuson et al., Volume E).

The effects of reduced ice cover and possible reduction in wetlands on Great Lakes fishes was not investigated, although Freeberg (1985) suggests that a reduction in ice cover would reduce whitefish recruitment, and Meisner et al. concluded that loss of wetlands due to lower lake levels could reduce spawning, nursery, and feeding grounds for fish in shallow areas, reducing fish populations (Meisner et al., 1987).

Implications

Fish populations could increase, with beneficial implications for commercial and recreational fishing, although certain species, such as brook trout in streams, may be reduced. A net increase in fisheries would lead to more employment in commercial fishing and tourism industries, but would increase the need for maintaining water quality in the lakes. Increased demand on the forage base by predators and the introduction of new species and reduced ice cover could have negative effects, but these cannot be predicted and must be considered as surprises of unknown probability.

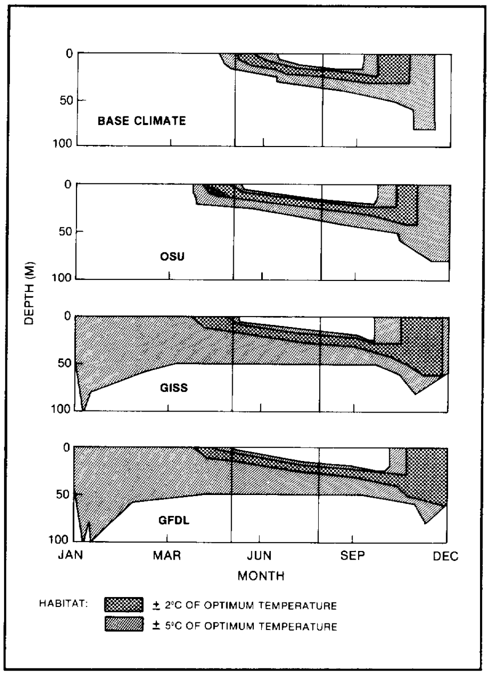

Figure 15-8. Increase in lake trout habitat (Magnuson et al., Volume E).

Forests

Climate change could affect the distribution and abundance of forests in the Great Lakes region. Overpeck and Bartlein examined the equilibrium range shift of forests, Botkin et al. studied transitional impacts on composition and abundance, and Zabinski and Davis analyzed the ability of trees to migrate along with a rapidly changing climate.

Potential Range Shifts

Study Design

Overpeck and Bartlein studied the potential shifts in ranges of forest types over eastern North America. This analysis suggests where trees are likely to grow in equilibrium doubled CO_2 climate conditions after allowing for migration of tree species to fully catch up with climate change (see Forest Migration). It indicates only the approximate abundance of different species within a range, not what the transitional effects of climate on forests might be, or how fast trees will be able to migrate to the new ranges. (For a discussion of the study's methodology and limitations, see Chapter 5: Forests.)

Results

Under all three doubled CO_2 scenarios, the range of spruce, a major component of the boreal forests, could shift almost entirely out of the region. Northern hardwoods, such as birch and northern pine species, would shift to the north but may still be in the region. Oak trees, which are mostly found in the southern part of the region, would be found all over the region in the warmer conditions. The abundance of prairie forbs (shrubs) would increase in the region, and southern pines could eventually migrate to the southern part of the region.

Transitional Effects

In contrast to Overpeck and Bartlein, Botkin et al. examined the transitional effect of climate change on forests as well as doubled CO_2 effects.

Study Design

Botkin et al. used a model of forest species growth and competition to estimate the effects of climate change on Great Lakes forests (Botkin et al., 1972, 1973). This model, which is known as a stand simulation model, can be used to estimate the transitional changes in composition and abundance of forest species in response to environmental changes such as higher temperature and precipitation.

Botkin et al. studied two diverse sites in the Great Lakes region. The first is in Mt. Pleasant, Michigan, a heavily settled area dominated by northern hardwoods and oaks, where commercial forests are an important resource. The other site is in Virginia, Minnesota, an undeveloped area dominated by boreal forests that have commercial and recreational uses.

Limitations

The model includes all dominant tree species in the northern United States and assumes that seeds from all these trees are universally available throughout the region. Species with predominantly southern distributions are not included; therefore, the model does not estimate whether they could grow in the region under the warmer climate. (Overpeck found that southern pines may migrate into the southern part of the region.) Thus, the stand simulation model does not accurately estimate migration of trees, either within the region or from other areas. Furthermore, the results do not assess whether transplantation by humans of more southern species would be successful. In addition, the model does not account for fertilization effects of CO_2, although CO_2 may not have positive effects in the competitive environment of unmanaged ecosystems (see Botkin et al., Volume D). Botkin et al.'s analysis did not account for introduction of new pests into the region, for the possibility of increased frequency of fires, or for the combined impact of changes in tropospheric air pollution levels and UV-B radiation.

Results

Botkin et al. estimated the doubled CO_2 climate would cause major changes in forest composition throughout the region. Results from the Mt. Pleasant site indicate that tree biomass at dry sites, which now have oak and sugar maple, could be reduced by 73 to 99% and could convert to oak savannas or even prairies. Relatively wet soil sites might be converted from sugar maple to mostly oak woodlands with some red maple. Biomass at these sites could be reduced by 37 to 77%.

In the Minnesota site, the boreal forests could be replaced by northern hardwood forests, now characteristic of areas to the south (see Figure 159). Relatively dry areas, such as the Boundary Waters Canoe Area where balsam fir dominates, and upland areas where white birch and quaking aspen dominate, could be replaced by forests consisting mainly of sugar maples. Where currently saturated soils in these upland areas become drier and better sites for tree growth, wood production may increase. However, bogs that now contain white cedar could become treeless. This is because no species that could tolerate warmer bog conditions are currently in the region. It is possible that more southern species could be transplanted to these

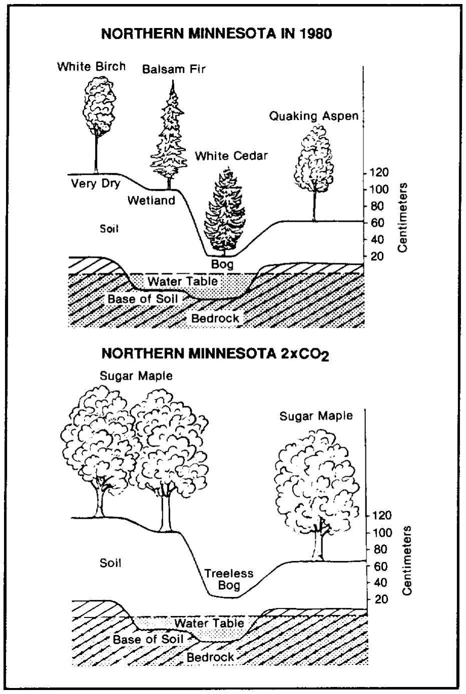

Figure 15-9. Changes in composition of northern Minnesota forests (Virginia, Minnesota; soil depth = 1.0 meter; water table depth = 0.8 meter) (Botkin et al., Volume D).

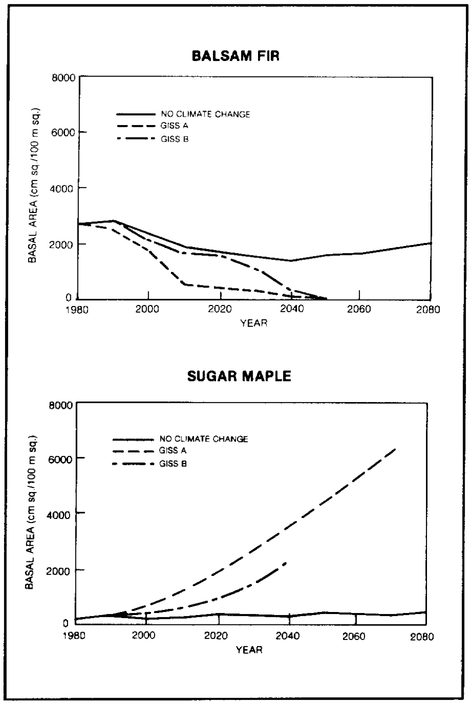

Figure 15-10. Change in forest composition during the next century for a deep, wet, sandy soil in northern Minnesota (Botkin et al., Volume D).

sites, although this was not studied.

In both sites, the biggest decline is seen in the hotter and drier GFDL scenario. Decreased soil moisture, which is a result of higher temperatures and reduced rainfall, appears to be the most significant factor reducing biomass.

Botkin et al. found that the abundance of species could significantly change in three to six decades. Figure 15-10 displays results from the transient scenarios for balsam fir and sugar maple at the Minnesota site. The basal area of balsam fir could start to decline in three to six decades. Potential declines in several decades are also seen in simulations of white cedar and white birch in the Minnesota site. Sugar maple, which has negligible basal area in the current climate, was estimated to start to exhibit significant growth within three decades in both transient scenarios.

Forest Migration

Both Overpeck and Botkin assumed that trees would be able to migrate to new locations (although Botkin did not assume southern species would be able to migrate into the Great Lakes region). Zabinski and Davis examined the potential range shifts of sugar maple, yellow birch, hemlock, and beech currently found in the Great Lakes region and compared that shift with potential rates of migration.

Study Design

Zabinski and Davis assumed that tree species grow only in climates with temperatures and precipitation identical to their current range. They determined the location of potential species ranges under the GISS and GFDL scenarios. The climate values were determined by extrapolating between gridpoints. Zabinski and Davis examined the potential migration of the species by assuming that the doubled CO_2 climate would not occur until 2090, and that these species could migrate into new regions at the rate of 100 kilometers (62 miles) per century.

Limitations

The study did not consider human transplantation of seedlings to speed migration. The analysis did not consider competition among species or whether migratory routes would be blocked. It also did not analyze whether species could survive in the soil conditions, nutrient availability, sunlight, and other relevant factors in northern areas. Doubled CO_2 climate conditions could occur sooner than 2090, resulting in greater range reductions. The rate of forest migration used is double the maximum rate ever recorded for temperate trees. A faster warming and slower migration would make it more difficult for forests to keep up with shifts in range attributable to climate change. Zabinski and Davis did not consider whether higher atmospheric CO_2 concentrations would mitigate the decline of forests along southern boundaries of their ranges.

Results

Under the wetter GISS scenario, the potential ranges of sugar maple, yellow birch, hemlock, and beech move markedly northward to central Canada. The results for hemlock and sugar maple are displayed in Figure 15-11. The stippled area shows the potential range, and the black area shows how far the trees could migrate by 2090. Zabinski and Davis found that hemlock, yellow birch, and sugar maple could become much less abundant in the parts of Wisconsin and Michigan where they currently grow. Beech may be completely eliminated from the lower peninsula of Michigan where it is presently abundant. In addition, the rate of migration would be slower than the climate change. The trees would not migrate as far as the northern boundary of the climate range (the stippled area). The southern boundary would be driven northward by climate change. Since the shift in climate zones is faster than the assumed rate of migration, the southern boundary would move north faster than the northern migration rates. The total range of all four species would be reduced.

Under the GFDL scenario, which is the hottest and driest, all four species are eliminated from the Great Lakes region. Northern hardwood tree species might be replaced by trees characteristic of more southern latitudes or by prairie or scrubland. Since the southern range of the trees moves farther north than in GISS, the inhabited range would be much smaller than under GISS. Zabinski and Davis found that all four tree species would be confined to an area in eastern Canada having a diameter of only several hundred kilometers. The ability of the four species to survive in more northern latitudes may depend on whether they could adapt to different day lengths and soils.

<u>Implications of Forest Studies</u>

All three studies, through different analytic approaches, agree that the scenarios of climate change would produce major shifts in forest composition and abundance. Boreal forests would most likely no longer exist in the region. Northern hardwood forests might still be present, especially in the north. Uncertainty exists concerning whether forests in the southern part of the region will die back leaving grasslands or whether new species will be able to migrate or will be transplanted and flourish. The rapid rate of climate change, coupled with the presence of urban areas and extensive farmland in the southern Great Lakes States, may impede migration of southern species into the region. Such a shift could result in increased soil erosion and decreased water quality. In addition, higher tree mortality and drier soils could increase fire frequency. There also may be an increase in pathogen-related mortality in trees. Shifts in forest composition and abundance may have implications for wildlife in the region.

This shift in species also could have significant impacts on the commercial forest industry in the region. The industry currently harvests softwoods for production of pulp, paper, and construction materials. These species would decline and would be replaced by oaks and maples, which are useful for furniture but take longer to become fully grown. Red maple, which may be more abundant in the southern area, is not currently used commercially. Changes in forest abundance may also affect tourism and recreation.

Agriculture

The agriculture studies combined analyses of impacts on the region and across the country. Ritchie et al. studied the potential impacts of climate change on crop yields in the region. Adams et al. then used the results from this study and other regional crop yield

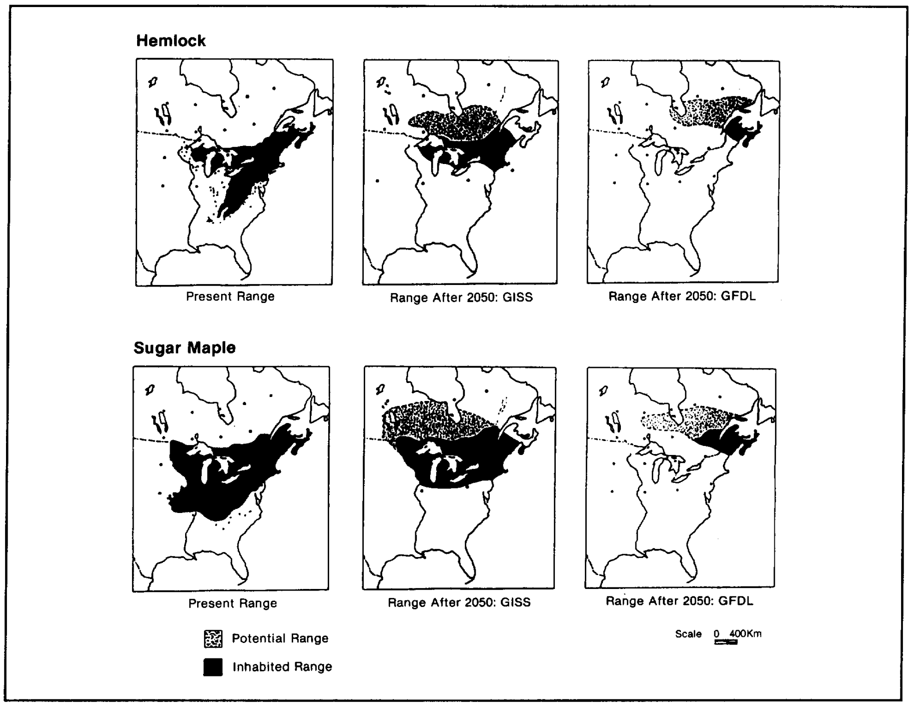

Figure 15-11. Shifts in range of hemlock and sugar maple (Zabinski and Davis, Volume D).

analyses to estimate economic adjustments by farmers. Easterling studied how a typical Illinois corn farmer would try to adapt to climate change.

Crop Yields

Study Design

Ritchie et al. used crop growth models to estimate the impacts of climate change on yields for corn and soybeans in the Great Lakes States (Jones and Kiniry, 1986; Wilkerson, 1983). The two physiological models examine the direct effects of temperature and precipitation on crop yields. Ritchie et al. also used simple estimates of increased photosynthesis and decreased transpiration to conduct a sensitivity analysis of the combined impacts of change in weather and CO_2 fertilization on crop yields. In addition, they studied whether crop varieties currently in southern areas may mitigate climate effects.

Limitations

The direct effects of CO_2 in the crop modeling study results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases, such as methane (CH_4) also are increasing, the equivalent warming of a doubled CO_2 climate may occur somewhat before an actual doubling of atmospheric CO_2. A level of 660 ppm CO_2, was assumed for the crop modeling experiments, while the CO_2 concentration in 2060 is estimated to be 555 ppm Hansen et al., 1988).

All the scenarios assumed that by having low salinity and no compaction, soils would be relatively favorable for crops, and there were would be no limits on the supply of all nutrients. In addition, the analysis assumed farmers would make no technological adjustments to improve crop yields or introduce new crops. Possible negative impacts due to changes in storm frequency, droughts, and pests and pathogens were not factored into this study. The results could be significantly affected by such changes. The percentage changes for Duluth are very large because current yields are very low relative to other sites.

Results

Ritchie et al. found that temperature and precipitation changes alone could reduce crop yields everywhere in the region, except in the northernmost latitudes, such as Duluth, where yields could increase depending on rainfall availability. Results from selected sites are displayed in Table 15-5. Corn yields could decrease from 3 to 60%, depending on climate and water regime (dryland or irrigated). However, Duluth, the most northern site, could see increases of 49 to 86%. Current dryland and irrigated corn yields are lower in Duluth than in the more southern sites. Dryland yields in Duluth under climate change could be equal to other sites, and irrigated yields could exceed the other locations.

Dryland soybean yields are estimated to drop by 3 to 65% in the region, except in the north. There, dryland yields may decrease by 6% under GFDL but increase by 109% under the wetter GISS. Under irrigated scenarios, soybean yields in the north increase by 96 to 153%. Even with the increase in output, the soybean yields in Duluth may still be lower than in areas to the south.

The reduction in yields in the south would be due mainly to the shorter growing period resulting from extreme summer heat. Production in the north is currently limited by the long winter, so a longer frost-free season results in increased yields.

Ritchie found that the demand for irrigation would rise between 20 and 173% under the GFDL scenario and up to 82% under GISS, although some sites under GISS were estimated to have reductions in demand of up to 21%.

The combined effects of higher concentrations of CO_2 and climate change could increase yields if sufficient rainfall is available. If it is not, yields could rise or fall. Dryland corn and soybean yields may rise up to 135% under the GISS scenario and up to 390% in Duluth. In the dry GFDL scenario, however, yields could fall up to 30% or rise up to 17%, again except for Duluth, which has an increase of 66 to 163%. Irrigated yields for corn rise and fall under both scenarios, but irrigated soybean yields could rise 43 to 72% in the south and up to 465% in Duluth. The combined effects lead to an estimated reduction in demand for irrigation for corn of 26 to 100% under both scenarios, whereas irrigation needs for soybeans under GFDL rise by 65 to 207% and range in GISS from a reduction of 10% to an increase of 32%.

Ritchie found that use of a longer season corn variety could reduce the negative effects of climate alone, under the GFDL scenario, but would still result in net losses.

It is not clear whether crop yields would rise or fall in the region. Among other factors, this will depend upon how CO_2 and climate change combine to affect crop growth and on how hot and dry the climate becomes. Yields and the potential demand for irrigation appear to be quite sensitive to rainfall, being higher under relatively drier scenarios. If climate change is severe enough, as under the GFDL scenario, yields could fall. In general, irrigation demand would rise, but some significant exceptions exist.

Implications

The potential shifts of agriculture northward are discussed below. Since the demand for irrigation is generally higher, it could become a more attractive option for farmers in the region. Whether more irrigation is actually used will depend on its costs and the price of crops.

Regional Shifts

Ritchie et al.'s analysis only estimates changes in potential yields for the Great Lakes region. How much farmers actually grow will depend in part on what happens elsewhere. If the relative productivity of agriculture rises, farmers will probably increase output. If relative productivity falls, they would most likely cut back. Adams et al. examined how different regions of the United States may react to potential productivity changes. Results are presented here for the Great Lakes region only.

Adams et al. modeled potential nationwide shifts in crops using the Great Lakes analysis and analyses of shifts in other regional crop yields. He did the analysis for yields attributable to climate change alone, and for the combined effects of climate and enhanced CO_2 concentrations. Adams et al.'s analysis did not account for the effects of climate on agriculture

Table 15-5. Effects of Climate Change Alone on Corn and Soybean Yields for Selected Sites in Great Lakes States (ranges are GISS-GFDL and are % change from base)

Site	Corn		Soybeans	
	Dryland	Irrigated	Dryland	Irrigated
Duluth, MN	+49 to -30	+86 to +36	+109 to -6	+153 to +96
Green Bay, WI	-7 to -60	-3 to -44	-3 to -65	+3 to -26
Flint, MI	-17 to -48	-14 to -38	-6 to -51	+6 to -11
Buffalo, NY	-26 to -47	-18 to -38	-21 to -53	+6 to -6
Fort Wayne, IN	-11 to -51	-15 to -48	-2 to -58	0 to -19
Cleveland, OH	-26 to -50	-19 to -43	-16 to -59	-1 to -14
Pittsburgh, PA	-22 to -55	-19 to -45	-13 to -59	0 to -13

Source: Ritchie et al. (Volume C).

in other countries. How U.S. and regional agriculture respond to climate change may be strongly influenced by changes in relative global productivity and demand. The study did not consider introduction of new crops such as citrus. (For a discussion of the study's design and limitations, see Chapter 6: Agriculture.)

Results

Adams et al.'s estimates of acreage changes for the Great Lakes States are shown in Table 15-6. It appears that land devoted to agriculture in the Great Lakes region would not change significantly in response to climate change. The results indicate a slight tendency to increase acreage in the northern Great Lakes States, although only by small amounts. Results for the Corn Belt States are inconclusive.

Table 15-6. Percentage Change in Acreage for Great Lakes States After Doubled CO_2 Climate Change (Corn Belt States include Iowa and Missouri)

Area	Climate change alone		Climate and CO_2	
	GISS	GFDL	GISS	GFDL
Lake States	+3	0	+1	+10
Corn Belt	+2	-6	-1	-6

Implications

The results of Adams et al. and Ritchie et al. suggest that northern regions could become more attractive for agriculture, although more extensive analysis is needed to confirm this result. The presence of thin, glaciated soils may limit this expansion. If it occurs, such an expansion could have significant implications for development of the north. Additional acreage could be converted from current uses, such as forests, to agriculture. Increased erosion and runoff from this additional acreage would pollute groundwater and streams and lakes in relatively pristine areas. Enhanced agriculture may increase the need for more shipping as lower lake levels raise shipping costs.

Adjustments by Illinois Corn Producers

Farmers may make many adjustments to climate change such as planting different crop varieties, planting earlier in the season, irrigating, and using different fertilizers. Easterling examined how a typical corn farmer in Illinois would react to climate change.

Study Design

Easterling presented several professional crop consultants with the GISS and GFDL climate change scenarios and with estimates of corn yields and prices for climate effects alone from the Ritchie et al. and

Adams et al. studies. Based on the interviews, a set of decision rules was established to estimate how a typical Illinois corn farmer would alter farming practices in response to the climate and agriculture scenarios.

Limitations

The climate change scenarios involve climate conditions not experienced by the experts. Their estimates of how farmers would respond are not based on experience with similar conditions but on speculation. The results of the combined climate and CO_2 sensitivity analyses were not presented to the experts. The analysis is specifically for Illinois corn farmers and cannot be extrapolated to other areas or crops.

Easterling found that the degree of adjustment depends on how much climate changes. Under the wetter GISS scenario, farmers could make adjustments to help mitigate the impacts of higher temperatures. Such adjustments could include planting earlier in the spring to avoid low soil moisture levels in the summer, using full-season corn varieties for earlier planting, and changing tillage practices and lowering planting densities to better conserve soil moisture. Under the hotter and drier GFDL scenario, corn production might not be feasible. Farmers would likely install irrigation systems; switch to short-season corn, soybeans, and grain sorghum; and perhaps remove marginal lands from production. This last conclusion is consistent with the Adams et al. study.

Implications

Although farmers have a variety of adjustment options to help cope with climate change, they may have great difficulty coping with extreme changes such as the dry climate implied by the GFDL scenario. Use of more irrigation would have negative implications for water quality, although this would be partly counterbalanced by any retirement of marginal lands.

Electricity Demand

Study Design

Linder and Inglis used the GISS transient scenarios to estimate the national changes in demand for electricity for the years 2010 and 2055. The temperature change for 2055 is almost as high as the GISS doubled CO_2 estimate of 4.2°C. They first estimated the change in electricity demand due to gross national product (GNP) and population growth, and then factored in demand changes based on change in climate. The results for the Great Lakes States are displayed here in terms of the percentage change from the non-climate-related growth. The Great Lakes analysis did not consider any reductions in hydropower production resulting from drops in lake levels. (For a description of the study's design and limitations, see Chapter 10: Electricity Demand.)

Results

Estimates of changes in annual demand induced by climate change are displayed in Table 15-7. The results for 2010 are a range based on GISS transient scenarios A and B, and the results for 2055 are just for GISS A. A latitudinal difference exists within the Great Lakes region. In the northern states of Minnesota, Wisconsin, Michigan, northern Ohio, and upstate New York, annual demand falls. The reduced demand for winter heating apparently offsets the increased demand for summer cooling. This is true in 2010 and 2055, when scenario temperatures are, respectively, 1 and 4°C higher than the base case. Annual demand in the southern part of the region (in Illinois, Indiana, southern Ohio, and Pennsylvania) was estimated to rise because increased cooling needs are apparently greater than reductions in heating.

Although annual demand could fall in some areas, new generation capacity requirements for all utilities in the region would be higher than they are now because of increased summer cooling needs. New generation capacity requirements needs are estimated to rise by 3 to 8% in 2010 and by 8 to 11% in 2055. Whether costs would rise in the next two decades is not clear. Linder and Inglis estimated that under the gradual warming of GISS B, cumulative capital costs in the region would be reduced by $1.3 billion, while under the more rapid warming of GISS A, costs would increase by $300 million. By 2055, costs would rise to $23 to $35 billion under GISS A. However, Linder and Inglis estimated that the cost to build additional capacity to meet GNP and population growth without climate change would be $488 to $715 billion.

Table 15-7. Estimated Changes in Electricity Demand Induced by Transient Climate Change Scenarios for Great Lakes Utilities (%)

Utility	Annual (2010)	Annual (2055)
Minnesota	-0.2 to -0.3	-1.2
Wisconsin	0.4 to -0.5	-2.3
Michigan	-0.2 to -0.3	-1.2
Upstate New York	-0.2 to -0.5	-1.3
Ohio, north	-0.2 to -0.3	-1.3
Ohio, south	0.4 to -0.5	2.1
Pennsylvania	0.4 to -0.5	2.2
Illinois	0.5	2.0
Indiana	0.4	1.9
Total	Negligible	<1

Source: Linder and Inglis (Volume H).

Implications

Increased capacity requirements could place additional stress on the region. Fossil fuel plants could add more pollutants to the air. The lake level analysis indicates that hydropower production from the lakes would be reduced, further increasing the demand for energy from other sources.

POLICY IMPLICATIONS

Climate change could raise many issues to be addressed by policymakers in the region. Fundamentally, decisionmakers may have to cope with water use, water quality, and land management issues. They could have to respond to a decline in water availability, increased demand for water, poorer water quality, and shifts in land use, including the possibility of expanded agriculture in the north.

Most likely, many of the decisions in response to climate change, especially issues concerning water management, would be made on an international basis. Both Canada and the United States oversee the regulation of the lakes, water quality, and diversions of water out of the basin.

Water Supply Issues

Lake Regulation

One important issue to be faced by both countries may be regulation of the lakes. Lower lake levels may require altering regulation plans for Lakes Superior and Ontario. This would involve tradeoffs among the needs of shippers, hydropower, shoreline property owners, and infrastructure, and downstream needs, in deciding how high to keep the lakes and rivers. For example, maintaining highwater levels in the lakes to support shipping, hydropower, consumption, and improved water quality would be at the expense of shipping, hydropower, municipal and industrial consumption, and water quality in the St. Lawrence River. Additional structures to control the flow on the lakes may be an option. The International Joint Commission should begin to consider in its long-term planning the potential impacts of climate change on lake regulations.

Withdrawals

Even without climate change, population growth would increase demand for water for municipal and industrial consumption and power generation. Climate change would most likely intensify the demand for withdrawals from the lakes for even more uses within and outside the basin. Municipal consumption would rise (Cohen, 1987b), and farmers in the region may need more water for irrigation.

Others outside the Great Lakes may demand diversion of water from the basin. The 1986 Water Resources Development Act prohibits such diversion without the agreement of all Great Lakes governors and prohibits the federal government from studying this issue. Increased diversion through the Chicago Ship Canal was requested in the summer of 1988 to raise water levels on the drought-starved Mississippi River. The U.S. Army Corps of Engineers rejected the request. Policy-makers will have to balance these demands with the needs of people in the basin.

Shipping

Any response to the potential impacts on the shipping industry may be costly. Possibilities include dredging of both ports and connecting channels. Dredging could cost tens, if not hundreds, of millions of dollars. In addition to the high capital costs of dredging, substantial environmental costs could be incurred in disposing of dredge soils contaminated with toxic chemicals. If dredging were not undertaken, cargo loads would be lower and would possibly impair Great Lakes commerce.

Pollution Control

Climate change could lead to stricter pollution control to maintain water quality. Reduced riverflow, lower lake levels, changed thermal structure, and potentially reduced groundwater supplies may necessitate stricter standards and additional controls on sources of pollution. A need may exist for better management of nutrient runoff from farms into shallow areas, such as the Lake Erie Western and Central Basins. Many pollution control institutions, such as EPA and state and local water quality agencies, would have the authority to impose appropriate controls on polluters.

The water quality problems directly caused by climate change could be exacerbated by other responses to climate change. Intensified agriculture in the region could increase runoff, necessitating more control of nonpoint sources of pollution. If agriculture in northern areas expands, surface and groundwater quality in relatively pristine areas may be degraded. Pollution control authorities such as the U.S. EPA may need to impose more comprehensive controls for those areas and should consider this in their long-term planning.

Fisheries

Although the analysis on fisheries indicates that fish populations in the Great Lakes would generally increase, maintaining fisheries may require intensive management. In productive areas, the possibility of introduction of new species could mean major changes in aquatic ecosystems. Fisheries management may be needed to maintain commercially and recreationally valuable species.

The Great Lakes Fishery Commission may wish to consider the possible implications of climate change on valuable fisheries and management strategies to handle these possible changes. Additional pollution controls may be needed to help maintain fisheries in such areas as western and central Lake Erie.

Land Use

Shorelines

The potential changes in land availability and uses present opportunities and challenges. Lower lake levels would open up new beaches and potential areas for recreation and development, although high capital costs may be associated with developing them. These lands could be kept undeveloped to serve as recreational areas and as protection against fluctuating lake levels and erosion. Conversely, they could be developed to provide more housing and commercial uses. Building structures closer to the shorelines would make them more vulnerable to short-term rises in lake levels.

How these lands will be used will be decided by local and state governments as well as private shoreline property owners. Under the Coastal Zone Management Act, states may identify coastal zone boundaries and define permissible land (and water) uses (Baldwin, 1984). Thus, the act could be used to help manage the use of exposed shorelines.

Lower lake levels and less ice cover may also increase shoreline erosion, decreasing the value of shorelines and degrading water quality. The Great Lakes Basin is not included in the U.S. coastal barrier system, a program that denies federal funds for development of designated erosion or floodprone coastal barriers (Ray et al., Volume J).

Forestry

The potential decline in forests and northward shift in Great Lakes agriculture raise many land-use issues. One important issue may be how to manage potentially large and rapid shifts in forest composition. To speed northward colonization, plantings of the species might be recommended along the advancing front of suitable climate. However, unsuitable soils and day lengths shorter than the species can tolerate might limit the success of such plantings. The forestry industry may consider growing different types of species and producing wood for different uses, such as for furniture rather than for pulp and paper.

Agriculture

Although forests may decline, demand for more land for agriculture in northern areas may grow; however, Adams et al. indicated this demand may be small and will depend on market forces and policies. Federal and state land managers as well as local zoning laws may need to consider that the demand for land use may change. Rules on these lands could have a major influence on how, if at all, the north is developed.

Demographic Shifts

This report did not study the demographics associated with climate change and cannot say whether people will migrate north along with warmer climates. A workshop on climate change and the Great Lakes region, conducted by Ray et al. and attended by government representatives, academics, and citizens group representatives who have studied climate-related Great Lakes resources, concluded that populations from other regions of the United States could migrate to the Great Lakes. The region could have a more favorable climate than more southern areas. Although lake levels may fall, the lakes will still contain a large amount of freshwater while other areas have more severe water availability problems. Consequently, the Great Lakes region may be relatively more attractive than other regions.

Like lower lake levels, an in-migration could present opportunities and challenges. Such a migration could revitalize the region, reversing population and economic losses of recent decades. However, it also could exacerbate some of the problems associated with climate change. More people and industries would require more water and add more pollution, further stressing water supplies and quality. Population growth could increase pressure to develop exposed shorelines along the lakes.

REFERENCES

Assel, RA., C.R. Snider, and R. Lawrence. 1985. Comparison of 1983 Great Lakes winter weather and ice conditions with previous years. Monthly Weather Review Vol. 113.

Baldwin, M.F. 1984. The Federal Government's role in the management of private rural land. Unpublished paper. p. 22.

Blumberg, A.F., and G.L. Mellor. 1983. Diagnostic and prognostic numerical circulation studies of the South Atlantic Bight. Journal of Geophysical Research 88:4579-4592.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1972. Rationale, limitations and assumptions of a northeast forest growth simulator. IBM Journal of Research and Development 16:101-116.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1973. Estimating the effects of carbon fertilization on forest composition by ecosystem simulation. In: Woodwell, G.M., and E.V. Pecan, eds. Carbon and the Biosphere. Brookhaven National Laboratory Symposium No. 24. Oak Ridge, TN: USAEC, pp. 328-344.

Cobb, C.E. Jr. 1987. The Great Lakes' troubled waters. National Geographic 172(1):2-31.

Cohen, S.J. 1986. The effects of climate change on the Great Lakes. In: Titus, J.G., ed. Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 3. Washington, DC: United Nations Environment Programme, U.S. EPA. pp. 163-183.

Cohen, S.J. 1987a. Sensitivity of water resources in the Great Lakes region to changes in temperature, precipitation, humidity, and wind speed. Proceedings of the Vancouver Symposium, August, 1987. IAHS Publ. No. 168.

Cohen, S.J. 1987b. Projected increase in municipal water use in the Great Lakes due to CO_2 induced climate change. Water Resources Bulletin 23(1):91-101.

Cohen, S.J., and Allsopp, T.R. 1988. The potential impacts of a scenario of CO -induced climatic change on Ontario, Canada. Journal of Climate 1(7):669-681.

Croley, T.E. II. 1983a. Great Lakes basins (U.S.A. to Canada) runoff modelling. Journal of Hydrology 64:135-158.

Croley, T.E. II. 1983b. Lake Ontario Basin (U.S.A. to Canada) runoff modeling. Journal of Hydrology 66:101-121.

Croley, T.E. II. 1988. Lumped Modeling of Laurentian Great Lakes Evaporation, Heat Storage and Energy Fluxes for Forecasting and Simulation. NOAA Technical Memo, ERL GLERL-XX, Environmental Research Laboratories, Boulder, CO. In press.

Crowder, L.B., and J.J. Magnuson. 1983. Costbenefit analysis of temperature and food resource use: a synthesis with examples from fishes. In: Aspey, W.P., and S.I. Lustick, eds. Behavioral Energetics. Columbus, OH: Ohio State University Press, pp. 189-221.

Crowe, R.B. 1985. Effect of Carbon Dioxide Warming Scenarios on Total Winter Snowfall and Length of Winter Snow Season in Southern Ontario. Atmospheric Environment Service - Canada. Unpublished manuscript.

Delay, W.H., and J. Seaders. 1966. Predicting temperatures in rivers and reservoirs. Journal of Sanitary Engineering 92:115-134.

DiToro, D.M., and J.P. Connolly. 1980. Mathematical Models of Water Quality in Large Lakes. Part 2: Lake Erie. Duluth, MN: U.S. Environmental Protection Agency. USEPA-600/380-065.

DiToro, D.M., NA. Thomas, C.S. Herdendorf, R.P. Winfield, and J.P. Connolly. 1987. A post audit of a Lake Erie eutrophication model. Journal of Great Lakes Research 134(4):801-825.

Edison Electric Institute. 1987. Statistical Yearbook of the Electric Utility Industry/1986. No. 54.

Eliot, J.L. 1985. A North Woods Park Primeval: Isle Royal. National Geographic 167(4):534-550.

Environment Canada. 1987. Implications of Climate Change for Navigation and Power Generation in the Lakes. Climate Change Digest CCD 87-03.

Federal Reserve Bank of Chicago and The Great Lakes Commission. 1985. The Great Lakes Economy: A Resource and Industry Profile of the Great Lakes States. Boyne City, MI: Harbor House Publishers, Inc.

Freeberg, M.H. 1985. Early life history factors influencing lake whitefish (Coreeonus clupcatormis) year-class strength on Grand Traverse Bay, Lake Michigan. Master of Science Degree Thesis. Michigan State University, Department of Fisheries and Wildlife, East Lansing, MI.

Garwood, R.W., Jr. 1977. An oceanic mixed layer model capable of simulating cyclic states. Journal of Physical Oceanography 7:455-468.

Great Lakes Basin Commission. 1975. Great Lakes Basin Framework Study: Appendixes 5, 11, 12, 13, and 19. Ann Arbor, MI: Public Information Office. Great Lakes Basin Commission.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone. 1988. Global climate changes as forecast by the Goddard Institute for Space Studies three dimensional model. Journal of Geophysical Research 93:9341-9364.

Horvath, F.J., M.R. Jannereth, and CA. Shafer. 1988. Impacts of Water Level Fluctuations. Water Science and Technology Board Colloquium Series, Great Lake Water Levels: Shoreline Dilemmas. Chicago, IL.

IJC. 1985. International Joint Commission. Great Lakes Diversions and Consumptive Uses. Report by International Great Lakes Diversion and Consumptive Uses Study Board. Washington, DC: International Joint Commission.

Jones, CA. and J.R. Kiniry, eds. 1986. CERESMaize: A Simulation of Maize Growth and Development. College Station, TX: Texas A&M Press.

Kitchell, J.F., D.J. Stewart, and D. Weininger. 1977. Applications of a bioenergetics model to yellow perch Perca flavescens) and walleye (Stizostedion vitreum). Journal of Fish Research 34:1922-1935.

Land Evaluation Group. 1986. Implications of Climatic Change and Variability for Ontario's Agrifood Sector. Prepared for Atmospheric Environment Service, Environment Canada. LEG26.

Larsen, C.E. 1985. Lake Level, Uplift, and Outlet Incision, the Nipissing and Algoma Great Lakes. Quaternary Evolution of the Great Lakes: Geological Association of Canada, Special Paper 30.

Linder, K.P., MJ. Gibbs, and M.R. Inglis. 1987. Potential Impacts of Climate Change on Electric Utilities. New York State Energy Research and

Development Authority, Albany, NY. Report 88-2.

Magnuson, J.J., L.B. Crowder, and PA. Medvicle. 1979. Temperature as an ecological resource. American Zoology 19:331-343.

Marchand, D., M. Sanderson, D. Howe, and C. Alpaugh. 1988. Climatic change and Great Lakes levels: the impact on shipping. Climatic Change 12:107-133.

Meisner, D.J., J.L. Goodier, H.A. Regier, B.J. Shuter, and W.J. Christie. 1987. An assessment of the effects of climate warming on Great Lakes Basin fishes. Journal of Great Lakes Research 13(3):340-352.

The New York Times. 1988. Out of mothballs, back on the lakes. p. 16. June 15.

Quinn, F.H. 1978. Hydrologic response model of the North American Great Lakes. Journal of Hydrology 37:295-307.

Quinn, F.H. 1988. Fluctuations of Great Lakes Water Levels. Water Science and Technology Board Colloquium Series, Great Lakes Water Levels: Shoreline Dilemmas. Chicago, IL.

Ruttner, F. 1931. Hydrographische and hydrochemische Beobachtungen auf Java, Sumatra and Vali. Arcluv for Hydrobiologic Supplement 8:197-454.

Sanderson, M. 1987. Implications of climatic change for navigation and power generation in the Great Lakes. Climatic Change Digest. Environment Canada Downsview, Ontario. CCD87-03.

Solomon, A.M., and D. West. 1986. Atmospheric carbon dioxide change: agent of future forest growth or decline? In: Titus, J., ed. Effects of Changes in Stratospheric Ozone and Global Climate. Washington, DC: United Nations Environment Program/U.S. Environmental Protection Agency. pp. 23-38.

Southam, C., and S. Dumont. 1985. Status Report. Impact of climate change on Great Lakes levels and outflows. Inland Waters Directorate. Ontario Region. Environment Canada Unpublished report.

Tarlock, DA. 1988. Multi-Jurisdictional Issues Presented to National Research Council, Water Science Technology Board Colloquium Series, Great Lakes Water Levels: Shoreline Dilemma. Chicago, IL. March.

U.S. Department of Commerce. 1987. U.S. Department of Commerce, Bureau of the Census. Statistical Abstract of the United States: 1987. (107th edition). Washington, DC: Government Printing Office.

U.S. Department of Commerce. 1983. U.S. Department of Commerce, Bureau of the Census. 1982 Census of Agriculture: Geographic Area Series. Washington DC: Government Printing Office.

USDA. 1987. U.S. Department of Agriculture. Agricultural Statistics. Washington, DC: U.S. Government Printing Office.

USDA. 1982. U.S. Department of Agriculture, Forest Service. An analysis of the timber situation in the U.S. 1952-2030. Washington, DC: U.S. Government Printing Office. Forest Resource Report No. 23.

U.S. EPA and Environment Canada. 1987. The Great Lakes: An Environmental Atlas and Resource Book. Chicago, IL.

Wall, G. 1985. Climate Change and Its Impact on Ontario Tourism and Recreation. Submitted to Environment Canada.

Wilkerson, G.G., J.W. Jones, K.J. Boote, K.J. Ingram, and J.W. Mishoe. 1983. Modeling soybean growth for crop management. Transactions of the American Society of Agricultural Engineers, St. Joseph, Michigan, 26:1, 63-73.

CHAPTER 16
SOUTHEAST

FINDINGS

Global climate change could diminish the extent of the region's forests, reduce agricultural productivity and increase the abandonment of farms, diminish fish and shellfish populations, and increase electricity demand. Approximately 90% of the national coastal wetland loss and two-thirds of the national shoreline protection costs from sea level rise could occur in the Southeast. The impacts on rivers and water supplies are uncertain.

Agriculture

- Southeastern agriculture is generally more vulnerable to heat stress than to freezing, so the adverse impacts of more hot days would more than offset the beneficial impact of a longer growing season.

- As a result of climate change alone, yields of soybeans and corn would vary from no change in the cooler regions to up to a 91% decrease in warmer areas, even if rainfall increases.

- A preliminary assessment suggests that when the direct effects of CO 2 are included, yields might increase in parts of the region if climate also becomes wetter. If climate becomes drier, yields could decrease everywhere in the region. However, our understanding of the direct effects of CO_2 fertilization is less certain than our understanding of the impacts of climate change. Increased CO_2 could also affect weeds, but these impacts were not analyzed.

- If rainfall decreases, irrigation will become necessary for farming to remain viable in much of the region.

- The range of such agricultural pests as potato leafhoppers, sunflower moths, and black cutworms could move north by a few hundred kilometers. This would most likely result in increased use of pesticides.

- Considering various scenarios of climate change and CO_2, the productivity of southeastern agriculture could decline relative to northern areas, and 10 to 57% of the region's farmland could be withdrawn from cultivation. This analysis did not consider whether new crops would be introduced. The decline in cultivated acreage may tend to be concentrated in areas where farming is only marginally profitable today. A reduction in agriculture could hurt farm-related employment and the regional economy.

Forests

- There may be a significant dieback in southern forests. Higher temperatures and drier soils may make it impossible for most species to regenerate naturally and may cause forests to convert to shrub terrain or grassland. The decline in the forests could be noticeable in 30 to 80 years, depending on the site and scenario. Southern noncoastal areas, such as Atlanta and Vicksburg, may have particularly large reductions. The moist coastal forests and the relatively cool northern forests may survive, although with some losses.

- The forest industry, which is structured around currently valuable tree species, would have to either relocate or modify its planting strategies.

- Historically, abandoned farms have generally converted to forests. If large portions of the Southeast lose the ability to naturally generate forests, much of the region's landscape may gradually come to resemble that of the Great Plains.

Water Supplies

Because the winter accumulation of snow plays a negligible role in determining riverflow, our inability to predict whether rainfall will increase or decrease makes it difficult to say whether riverflows will increase or decrease.

- The limited number of hydrologic studies conducted in the Southeast further prevents us from making any definitive statement about the regionwide implications for rivers.

- Decreases in rainfall could disrupt navigation, drinking water availability, recreation, hydropower, powerplant cooling, and dilution of effluent, while increased rainfall could exacerbate the risk of flooding.

- For the scenarios used in this report, changes in operating rules for managed water systems would allow current water demands to be met in most instances.

- The Southeast generally has ample groundwater supplies. The potential implications of increased irrigation on groundwater need to be examined.

Sea Level Rise

- A 1-meter rise in sea level by the years 2100 would inundate 30 to 90% of the region’s coastal wetlands and flood 2,600 to 4,600 square miles of dryland, depending on the extent to which people erect levees to protect dryland from innundation. If current river management practices continue, Louisiana alone would account for 40% of national wetland loss, and developed areas could be threatened as soon as 2025.

- Holding back the sea by pumping sand or other measures to raise barrier islands, and protecting mainland areas with bulkheads and levees, would cost approximately $42 to $75 billion through the year 2100 for a 1-meter rise.

Marine Fisheries

- Gulf coast fisheries could be negatively affected by climate change. A loss of coastal wetlands due to sea level rise could eliminate the critical habitats for shrimp, crab, and other commercially important species. Temperatures in the gulf coast estuaries may exceed the thermal tolerances for commercially important finfish and shellfish, such as shrimp, flounder, and oysters. Oysters and other species could be threatened by the increased salinity that will accompany sea level rise. Some species, such as pink shrimp and rock lobster, could increase in abundance.

Electricity Demand

The annual demand for electricity in the Southeast could rise by 14 to 22 billion kilowatthours (kWh), or 2 to 3%, by 2010 and by 100 to 197 billion kWh, or 7 to 11%, by 2055 as a result of increased temperature.

By 2010, approximately 7 to 16 gigawatts (GW) could be needed to meet the increased demand, and by 2055, 56 to 115 GW could be needed -- a 24 to 34% increase over baseline additions that may be needed without climate change. The cumulative costs could be $77 to $110 billion by 2055.

Policy Implications

- Federal laws constrain the U.S. Army Corps of Engineers and other water resource managers from rigorously considering tradeoffs between may nonstatutory objectives of federal dams in the Southeast, including recreation, water supply, and environmental quality. Increased flexibility would improve the ability of these agencies to respond to and prepare for climate change.

- Given the potential withdrawals of acreage from agriculture, the potential for growing tropical crops needs to be examined.

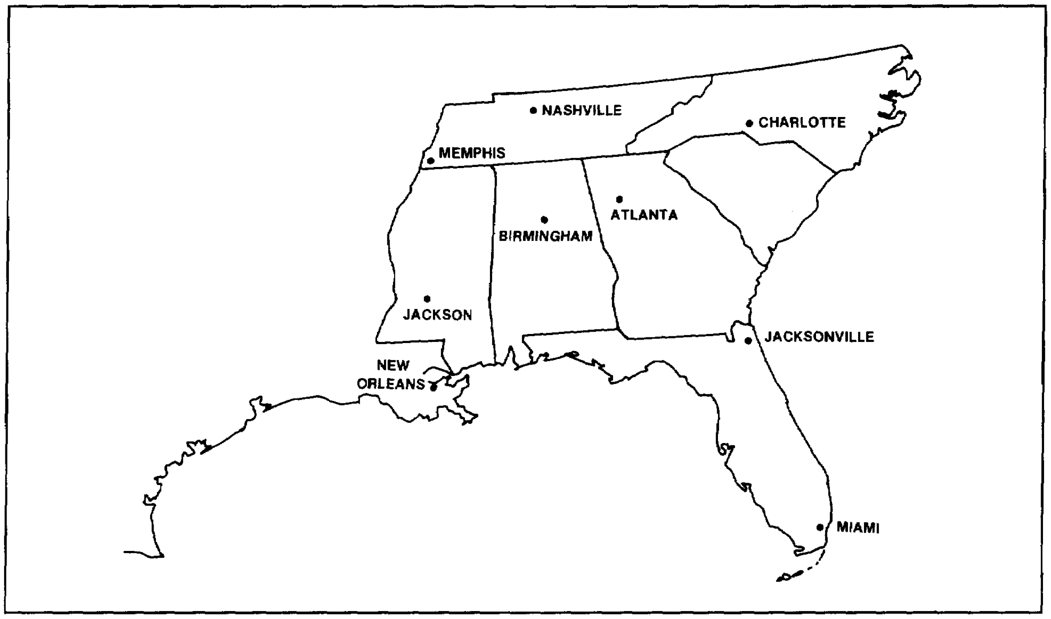

Figure 16-1. Southeast region.

- Strategies for now being evaluated by the Louisiana Geological Survey and the U.S. Army Corps of Engineers to address coastal wetland loss in Louisiana should consider a possible sea level rise of 0.5 to 2.0 meters. measures that would enable this ecosystem to survive would require major public works and changes in federal navigation and riverflow policies. Because of the decades required to implement necessary projects and the prospect that much of the ecosystem would be lost by 2030 even without climate change, these programs need to proceed expeditiously.

- Given the potentially important impacts on forests, private companies as well as agencies such as the U.S. Forest Service and state agencies may wish to assess the potential for large losses of southern forests and the implications for research and management strategies.

CLIMATE AND THE SOUTHEAST

The climate and the coastal zone of the Southeast are among the chief factors that distinguish the southeastern United States from the rest of the nation[1]. The warm temperatures, abundant rainfall, and generally flat terrain gave rise in the 17th century to a strong agricultural economy with a distinctive regional culture. The combination of a benign climate and 60% of the nation's ocean beaches continues to attract both tourists and new residents to the southeastern coastal plain. Florida, for example, is the nation's fastest growing state and will be the third largest by the year 2000 (Meo et al., Volume J).

CLIMATE-SENSITIVE RESOURCES OF THE SOUTHEAST

Water Resources

When statewide averages are considered, each of the seven states in the Southeast receives more rainfall than any other state in the continental United

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[1] Except for the discussion of the economic implications for agriculture, the term "Southeast" refers to the study area shown in Figure 16-1: North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, and the coastal zones of Louisiana and Texas.

States (although parts of some western states receive more). Moreover, the rivers of the Southeast drain over 62% of the nation's lands; the Mississippi River alone drains 38% of the nation (Geraghty et al., 1973).

The Southeast supports 50,000 square miles of bottomland hardwood forests (Mitch and Gosselink, 1986)[2], which are periodically flooded areas that offer winter habitat for migratory birds such as ducks, geese, and songbirds. Bass, catfish, and panfish are found in the slow-moving rivers, and trout inhabit the fast-moving mountain streams.

Dams have been constructed along most of the region's major rivers. Although private parties have built a few dams, most of the major projects were built by the U.S. Army Corps of Engineers, the Tennessee Valley Authority, and other federal agencies. In general, the statutory purposes of these reservoirs have been to ensure a sufficient flow of water during droughts, to prevent floods, and to generate electricity. The non-statutory objectives of environmental quality, recreation, and water supply also are considered in the operation of dams.

Dam construction has created large lakes along which people have built houses, hotels, and marinas. These dams generate 22.2 billion kilowatthours (kWh) per year, approximately 7% of the region's power requirements (Edison Electric Institute, 1985). In general, the reservoirs have sufficient capacity to retain flood surges and to maintain navigation flows during the dry season. The one notable exception is the Mississippi River: levees and land-use regulations are the main tools for preventing flood damages; although the Mississippi's base flow usually is sufficient to support navigation, boats ran aground on many stretches of the river during the drought of 1988.

In Florida, which accounts for 45% of water consumption in the Southeast, groundwater supplies about half the water used by farms and 85% of the water used for residential and industrial purposes. For the rest of the Southeast, groundwater supplies most water for agricultural and rural uses but only 30% for public supplies (see Meo et al., Volume J).

Atlanta and some other metropolitan areas obtain their water supplies from federal reservoirs; however, even the many cities that do not still may benefit from federal and federal/state water management. For example, New Orleans obtains its water from the Mississippi River. Without the Old River Control Structure in Simmesport, Louisiana, which prevents the river from changing its course to the Atchafalaya River, the New Orleans water supply would be salty during droughts. Although Miami obtains its water from the Biscayne Aquifer, some coastal wells would be salty without the efforts of the U.S. Army Corps of Engineers and the South Florida Water Management District to recharge the aquifer with supplemental freshwater from canals and Lake Okeechobee.

The various uses of water often conflict with each other. Hydroelectric power generators, lakefront residents, and boat owners benefit when water levels are maintained at high levels. However, high water levels make flood control more difficult, and municipal uses, navigation, hydropower, and environmental quality require that water be released during the dry season, which adversely affects recreation.

Estuaries

Over 43% of the fish and 70% of the shellfish harvested in U.S. waters are caught in the Southeast (NOAA, 1987). Commercially important fishes are abundant largely because the region has over 85% of the nation's coastal wetlands; over 40% are in Louisiana alone.

Most of the wetlands in the Southeast are less than 1 meter above sea level. The wetlands in Louisiana are already being lost to the sea at a rate of 50 square miles per year because of the interaction of human activities and current rates of relative sea level rise resulting from the delta's tendency to subside 1 centimeter per year. (This problem is discussed in greater detail below.)

Summer temperatures in many of the gulf coast estuaries are almost as warm as crabs, shrimp, oysters, and other commercially important fishes can tolerate (Livingston, Volume E). Winter temperatures along the gulf coast are almost warm enough to support mangrove swamps, which generally replace marshes

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[2] This measure includes Mississippi, Arkansas, Louisiana, Texas and Virginia.

once they are established; mangroves already dominate the Florida coast south of Fort Lauderdale.

Beach Erosion and Coastal Flooding

The Southeast has 1,100 miles of sandy ocean beaches, many of which are found on low and narrow barrier islands. The Atlantic coast is heavily developed, while much of the gulf coast is only now being developed. In part because of their vulnerability to hurricanes, none of Mississippi's barrier islands has been developed, and only one of Louisiana's barrier islands is developed at present. Because much of Florida's gulf coast is marsh, it is still largely undeveloped.

All eight coastal states are experiencing coastal erosion. Along developed coasts, recreational beaches have narrowed, increasing the vulnerability of shorefront structures to storms. In Louisiana, some undeveloped barrier islands are eroding and breaking up. Elsewhere, narrow barrier islands are keeping pace with sea level rise by "overwashing" (i.e., rolling over like a rug) in a landward direction, while wide islands and mainland coasts have simply eroded. The coastal states of the Southeast are responding by holding back the sea in some areas and by adapting to erosion in others.

The two greatest natural disasters in U.S. history resulted from floods associated with hurricanes in Galveston, Texas, and Lake Okeechobee, Florida, in which over 8,000 people drowned. After the Mississippi River overflowed its banks and inundated most of coastal Louisiana in the 1930s, Congress directed the U.S. Army Corps of Engineers to initiate a major federal program of flood control centered around the Southeast. Nevertheless, flood waters often remain over some low areas in Louisiana and Florida for several days after a major rainstorm.

Hurricanes continue to destroy recreational development in at least a few ocean beach communities almost every year in the Southeast. The region presently experiences the majority of U.S. coastal flooding and probably would sustain the worst increases in flooding as a result of global warming. Unlike the Northeast and Pacific coasts, this region has wide low-lying coastal plains and experiences several hurricanes annually. Florida, Texas, and Louisiana account for 62% of the $144 billion of private property insured by the Federal Flood Insurance Program (see Riebsame, Volume J).

Agriculture

In the last few years, droughts and heat waves have caused crop failures in many parts of the Southeast. Unlike much of the nation, cold weather generally is not a major constraint to agricultural production, except for Florida's citrus industry.

Although cotton and tobacco were once the mainstays of the Southeast's economy, agriculture now accounts for only 1% of the region's income (U.S. Department of Commerce, 1986). Since World War II, substantial amounts of farmland have been withdrawn from agriculture, and much of thus land has been converted to forest. The cotton crop has been largely lost to the irrigated Southwest, and although tobacco remains profitable, it is grown on only 500,000 acres. However, in the last few decades, southeastern farmers have found soybeans to be profitable; this crop now accounts for 45% of all cultivated land in the Southeast. Corn continues to account for 5% of southeastern agriculture U.S. Department of Commerce, 1982). Table 16-1 compares annual revenues by state for various crops.

Forests

The commercial viability of southeastern forests has increased greatly since World War 11, primarily as a result of the increased use of softwoods, such as pines and firs, for plywood and for applications that once required hardwood. Because this transition coincided with lower farm prices and declining soils in the piedmont foothills of the Southeast, many mountain farms have been converted to forests. However, in the last 10 years, 7 million acres of coastal plain forests have been converted to agriculture (Healy, 1985).

Approximately 45% of the nation's softwood (mostly loblolly pine) and 50% of its hardwood are grown in the region. Forests cover 60% of the Southeast, and 90% of forests are logged. Oak-hickory covers 35%, and pine covers another 33% of commercial forests. Only9% of the southeastern forests are owned by federal and state governments, and 18% are owned by the forest industry. In contrast, 73% of the forests are owned by farmers and other private parties (Healy, 1985).

Table 16-1. Annual Revenues by State for 33% of commercial forests. Only 9% of the Various Crops (thousands of 1986 southeastern forests are owned by federal and state dollars)

Crop	Value
Corn for grain	
Alabama	856,550
Florida	31,493
Georgia	203,931
Mississippi	22,600
North Carolina	324,789
South Carolina	104,333
Tennessee	193,687
Cotton	
Alabama	145,540
Florida	8,112
Georgia	97,325
Mississippi	449,630
North Carolina	30,944
Tennessee	109,610
Sugarcane for sugar and seed	
Florida	369,899
Tobacco	
Florida	NA
Georgia	NA
North Carolina	NA
South Carolina	NA
Tennessee	NA
Peanuts for nuts	
Alabama	133,930
Florida	48,600
Georgia	472,645
North Carolina	122,941
South Carolina	5,882
Soybeans	
Alabama	140,719
Florida	31,036
Georgia	179,676
Mississippi	365,018
North Carolina	196,673
South Carolina	125,214
Tennessee	230,373

NA= Not Available.
Source: U.S. Department of Agriculture (1987).

Indoor and Outdoor Comfort

The southeast is one of the few areas that spends as much money on air-conditioning as heating. Figure 16-2 shows temperatures throughout the Southeast for the months of January and July. Even in January, about half the region experiences average temperatures above 50°F. Thus, with the possible exception of the cool mountains of Tennessee and North Carolina, a global warming would increase the number of days during which outdoor temperatures would be unpleasantly hot much more than it would reduce the number of unpleasantly cold days.

PREVIOUS STUDIES OF THE IMPACTS OF CLIMATE CHANGE ON THE SOUTHEAST

Most studies examining the impact of global warming on the Southeast have focused on sea level rise. Recent efforts have addressed other topics. Several dozen researchers presented papers on other global warming impacts on the Southeast at a 1987 EPA conference held in New Orleans (Meo, 1987). Their papers suggested that agricultural yields would decline, forest species would shift, and that coastal and water supply officials should start to plan for the consequences of global warming.

Flooding

Leatherman (1984) and Kana et al. (1984) applied flood-forecasting models to assess potential increases in flooding in Galveston, Texas, and Charleston, South Carolina. For the Galveston area, a 90-centimeter (3-foot) rise would increase the 100-year floodplain by 50%, while a 160-centimeter (5.2-foot) rise would enable the 100-year storm to overtop the seawall erected after the disaster of 1900. For the Charleston area, a 160-centimeter rise would increase the 10-year floodplain to the area currently covered by the 100year floodplain.

Gibbs (1984) estimated that the economic impact of a 90-centimeter rise by 2075 could be as great as $500 million for Galveston and over $1 billion for Charleston. However, he also estimated that the adverse impacts of flooding and land loss could be cut in half if the communities adopted measures in anticipation of sea level rise. Titus (1984) focused on decisions facing

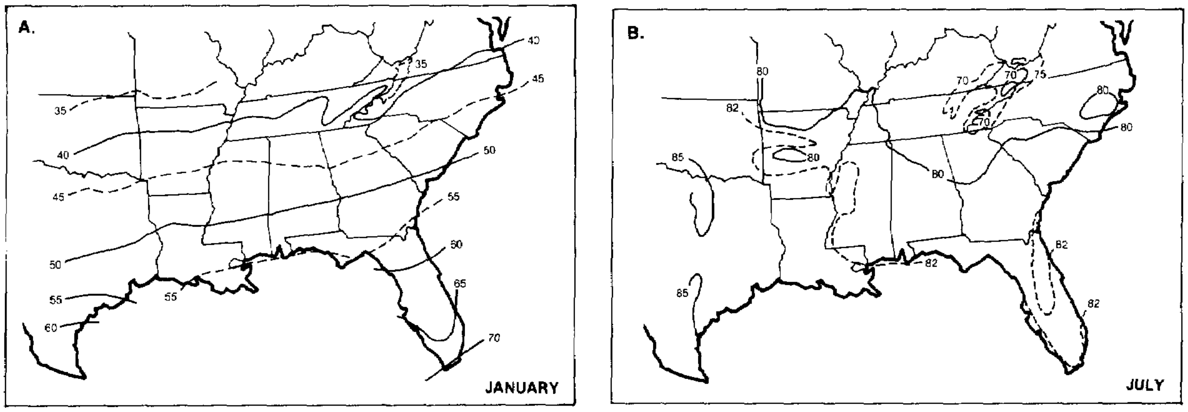

Figure 16-2. Typical temperatures in the Southeast: (A) January, (B) July.

Sullivans Island, South Carolina, in the aftermath of a storm. He concluded that rebuilding $15 million in oceanfront houses after a storm would not be economically sound if future sea level rise is anticipated, unless the community is prepared to continuously nourish its beaches.

Wetlands

Kana et al. (1986) surveyed marsh transects and estimated that 90- and 160-centimeter (3.0- and 5.2-foot) rises in sea level would drown 50 and 90%, respectively, of the marsh around Charleston, South Carolina. Armentano et al. (1988) estimated the Southeast would lose 35 and 70% of its coastal wetlands for respective rises of 1.4 and 2.1 meters, assuming that developed areas are not protected.

Infrastructure

The Louisiana Wetland Protection Panel (1987) concluded that a rise in sea level might necessitate substantial changes in the ports and shipping lanes of the Mississippi River to prevent the loss of several thousand square miles of coastal wetlands. Titus et al. (1987) showed that a reconstructed coastal drainage system in Charleston should be designed for a 1-foot rise in sea level if the probability of such a rise is greater than 30%. Linder et al. (1988) found that warmer temperatures would require an electric utility company to substantially increase its generating capacity.

CLIMATE CHANGE STUDIES IN THIS REPORT

Table 16-2 and Figure 16-3 illustrate the studies undertaken as part of this effort. Few resources had previously been applied to examining the various impacts of climate change for the Southeast. Models of coastal erosion, coastal wetland loss, agricultural yields, forest dynamics, and electricity consumption were sufficiently refined, so that it was possible to inexpensively apply them to numerous sites and develop regional assessments. Louisiana, which accounts for half of the region's wetlands, has been the subject of previous studies. It is discussed following the studies for this report.

By contrast, the impacts on water resources and ecosystems required more detailed site-specific studies, and it was not possible to undertake such case studies for a large number of watersheds or ecosystems. Therefore, our analysis was limited to representative case studies. For water resources, we picked (1) the Tennessee Valley, because it is the largest managed watershed in the region; and (2) Lake Lamer, because it serves Atlanta, the region's second largest city. In both cases, we were able to identify researchers who were already familiar with the area. The sole aquatic ecosystem studied in depth was Apalachicola Bay, picked because the estuary had already been the subject of the most comprehensive data collection effort in the Southeast.

Table 16-2. Studies of the Southeast

Regional Studies

- Impacts on Runoff in the Upper Chattahoochee River Basin - Hains, C.F. Haines, Hydrologist, Inc. (Volume A)
- Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration - Livingston, Florida State University (Volume E)
- Policy Implications of Global Climatic Change Impacts Upon the Tennessee Valley Authoriy Reservoir System, Apalachicola River, Estuary and Bay and South Florida - Meo, Ballard, Deyle, James, Malysa, and Wilson, University of Oklahoma (Volume J)
- Potential Impacts on Climatic Change on the Tennessee Valley Authority Reservoir System -Miller and Brock, Tennessee Valley Authority (Volume A)
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A. - Peart, Jones, and Curry, University of Florida (Volume C)
- Methods for Evaluating the Potential Impacts of Global Climate Change - Sheer and Randall, Water Resources Management, Inc. (Volume A)
- Forest Response to Climate Change: A Simulation Study for Southeastern Forests - Urban and Shugart, University of Virginia (Volume D)

National Studies That Included Southeast Results

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment - Adams, Glyer, and McCarl, Oregon State University (Volume C)
- National Assessment of Beach Nourishment Requirements Associated with Accelerated Sea Level Rise - Leatherman, University of Maryland (Volume B)
- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates -Linder and Inglis, ICF Inc. (Volume H)
- The Effects of Sea Level Rise on U.S. Coastal Wetlands -Park and Trehan, Butler University and Mausel and Howe, Indiana State University (Volume B)
- Potential Effects of Climatic Change on Plant-Pest Interactions - Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center (Volume C)
- Assessing the Responses of Vegetation to Future Climate Change: Ecological Response Surfaces and Paleoloocal Model Validation - Overpeck and Bartlein, Lamont-Doherty Geological Observatory (Volume D)
- An Overview of the Nationwide Impacts of Rising, Sea Level - Titus and Greene, U.S. Environmental Protection Agency (Volume B)
- The Cost of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two Meter Rise in Mean Sea Level - Weggel, Brown, Escajadillo, Breen, and Doheny, Drexel University (Volume B)

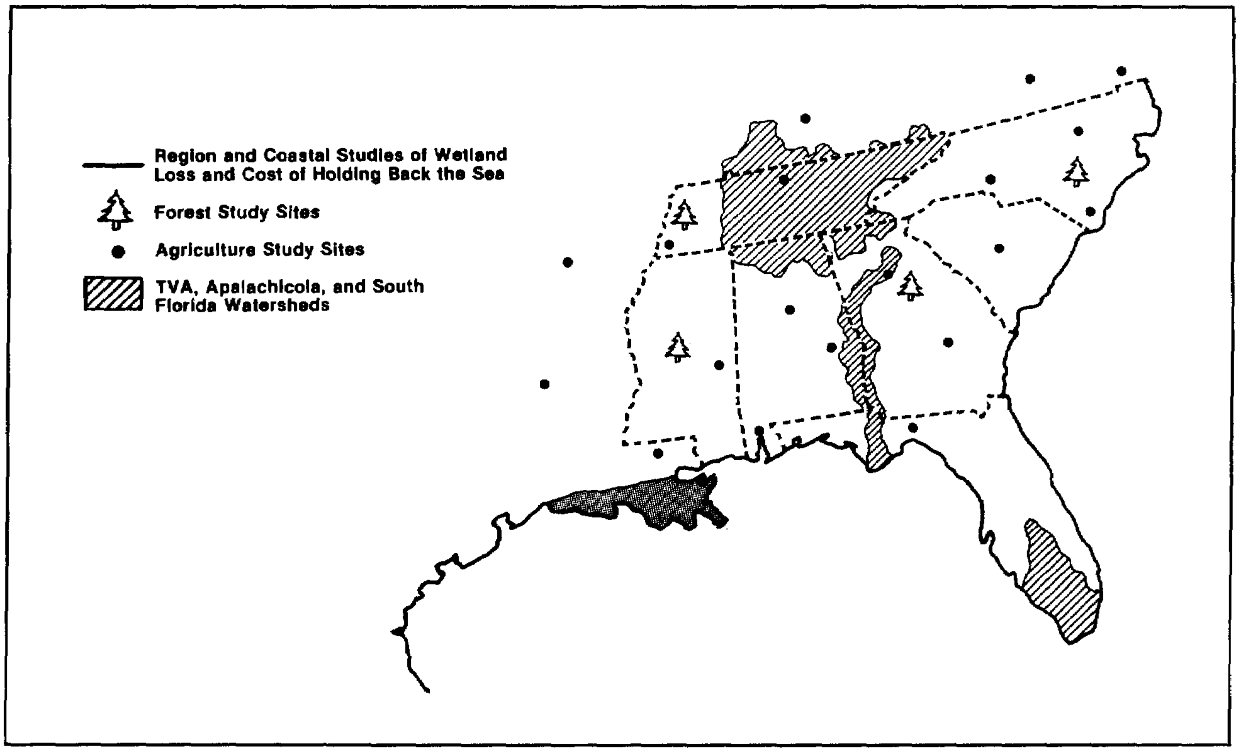

Figure 16-3. Overview of studies of the Southeast.

SOUTHEAST REGIONAL CLIMATE CHANGE SCENARIOS

Figure 16-4 illustrates the scenarios of future climate change from general circulation models. Table 16-3 shows the more detailed seasonal changes.

Table 16-3 illustrates how the frequency of mild days during the winter and the frequency of very hot days during the summer might change under the Goddard Institute for Space Studies (GISS) doubled CO_2 scenario. As explained in Chapter 4: Methodology, these estimates used average monthly changes in temperature and assumed no change in variability. Under this scenario, the number of days per year in which the mercury would fall below freezing would decrease from 34 to 6 in Jackson, Mississippi; from 39 to 20 in Atlanta; and from 41 to 8 in Memphis. The number of winter days above 70°F would increase from 15 to 44 in Jackson, from 4 to 14 in Atlanta, and from 5 to 24 in Memphis.

Of the nine cities shown, only Nashville has summer temperatures that currently do not regularly exceed 80°F. However, the number of days with highs below 80°F would decline from 60 to 34. Elsewhere, the heat would be worse. The number of days per year above 90°F would increase from 30 to 84 in Miami, from 17 to 53 in Atlanta, and from 55 to 85 in New Orleans. Memphis, Jackson, New Orleans, and Jacksonville, which currently experience 0 to 3 days per year above 100°F, would have 13 to 20 such days (Kalkstein, Volume G).

RESULTS OF SOUTHEASTERN STUDIES

Coastal Impacts

A number of national studies for the report presented results for the effects of climate change on the southeastern coast. Leatherman estimated the cost of maintaining recreational beaches. Park et al. and Weggel et al. examined the impacts on wetland loss and shoreline defense, and used their results to estimate the regionwide cost of raising barrier islands. The projected

Table 16-3. The GISS Doubled $_{CO2}$ Scenario: Frequency of Hot and Cold Days (°F)

Location	Number of winter days with:				Number of summer days with:					
	Daily low <32		Daily high >70		Daily high <80		Daily high >90		Daily high >100	
	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$
Atlanta, GA	38.3	20.5	4.2	13.6	10.0	2.2	17.1	53.3	0.6	4.2
Birmingham, AL	35.5	8.1	7.1	30.7	4.5	0.4	34.1	72.5	1.5	10.7
Charlotte, NC	42.1	23.8	3.4	9.9	11.9	3.7	23.1	56.5	0.1	5.9
Jackson, MS	33.5	5.9	15.3	43.5	0.8	0.2	55.1	83.1	2.0	19.5
Jacksonville, FL	9.3	1.7	34.6	49.6	2.3	0.3	46.4	81.3	0.6	14.1
Memphis, TN	41.2	8.1	5.2	23.6	4.9	0.7	50.5	74.8	2.6	19.1
Miami, FL	0.2	0.0	72.9	82.7	0.6	0.0	29.8	83.5	0.0	2.5
Nashville, TN	42.5	15.4	0.3	8.6	60.4	33.7	10.5	20.2	0.3	3.5
New Orleans, LA	14.9	3.5	24.9	39.5	0.9	0.1	55.4	84.9	0.3	13.5

HIST[a] = Historic.

Source: Kalkstein (Volume G).

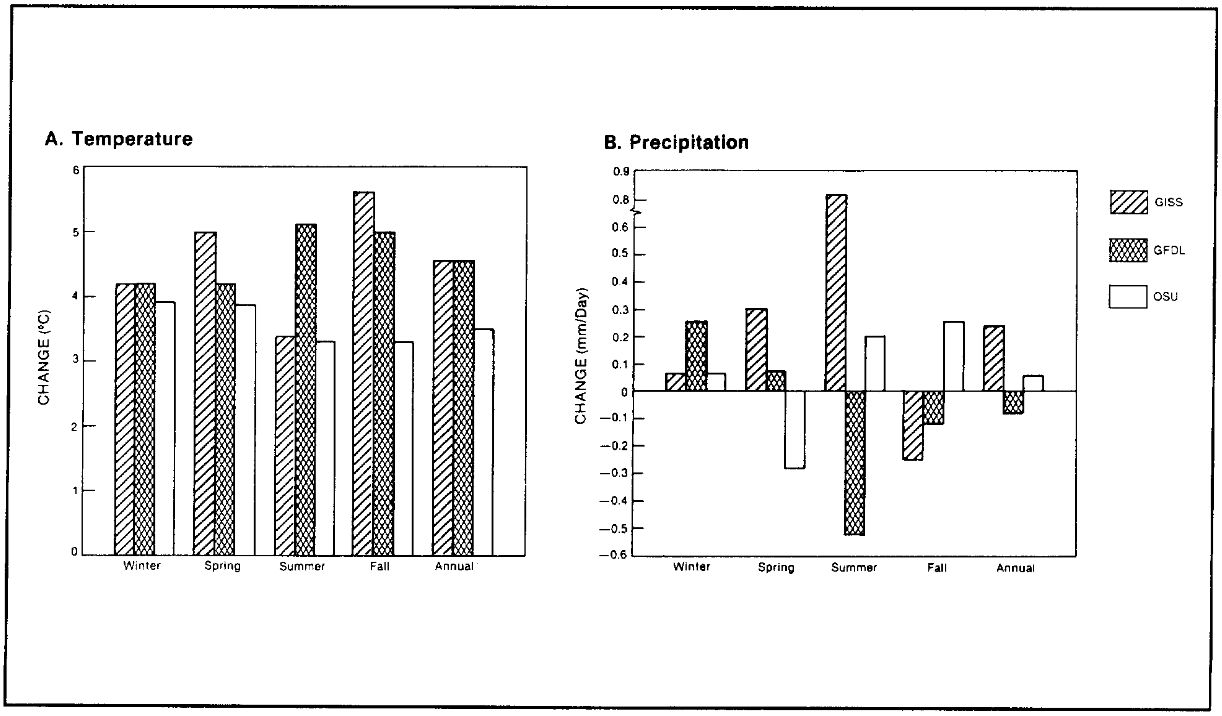

Figure 16-4. $2xCO_2$ less $1XCO_2$ climate scenarios for the Southeast: (A) temperature, and (B) precipitation..

rise in sea level would cause shorelines to retreat, exacerbate coastal flooding, and increase the salinity of estuaries, wetlands, and aquifers. (For a discussion of the rationale, methods, and nationwide results of these studies, see Chapter 7: Sea Level Rise.)

Coastal Wetlands

Park et al. (Volume B) examined 29 southeastern sites to estimate the regionwide loss of coastal wetlands for a variety of scenarios of future sea level rise. Their analyses included such societal responses as providing structural protection for all shorelines (total protection), protecting areas that are densely developed today (standard protection), and allowing shorelines to adjust naturally without coastal protection (no protection).

Figure 16-5 illustrates their estimates for the year 2100 for the various scenarios of sea level rise and coastal defense. Even if current sea level trends continue, 25% of the Southeast's coastal wetlands will be lost, mostly in Louisiana. Excluding Louisiana:

- current trends imply a loss of 15%;
- a 50-centimeter rise could result in a loss of 35 to 50%, depending on how shorelines are managed;
- a 100-centimeter rise could result in losses of 45 to 68%; and
- a 200-centimeter rise implies losses of 63 to 80%.

Park et al. estimated losses of 50, 75, and 98% for Louisiana under the three scenarios. However, they did not consider the potential for mitigating the loss by restoring the flow of river water into these wetlands; no model exists that could do so (Louisiana Wetland Protection Panel, 1987). Titus and Greene estimated statistical confidence intervals illustrated in Table 16-4.

Total Coastal Land Loss

Park et al. also estimated total land loss, including both wetlands and dryland. Most of the land loss from a rise in sea level would occur in Louisiana. A 50-centimeter (20-inch) sea level rise would result in the loss of 1,900 to 5,900 square miles of land, while a 200-centimeter rise would inundate 10,000 to 11,000 square miles.

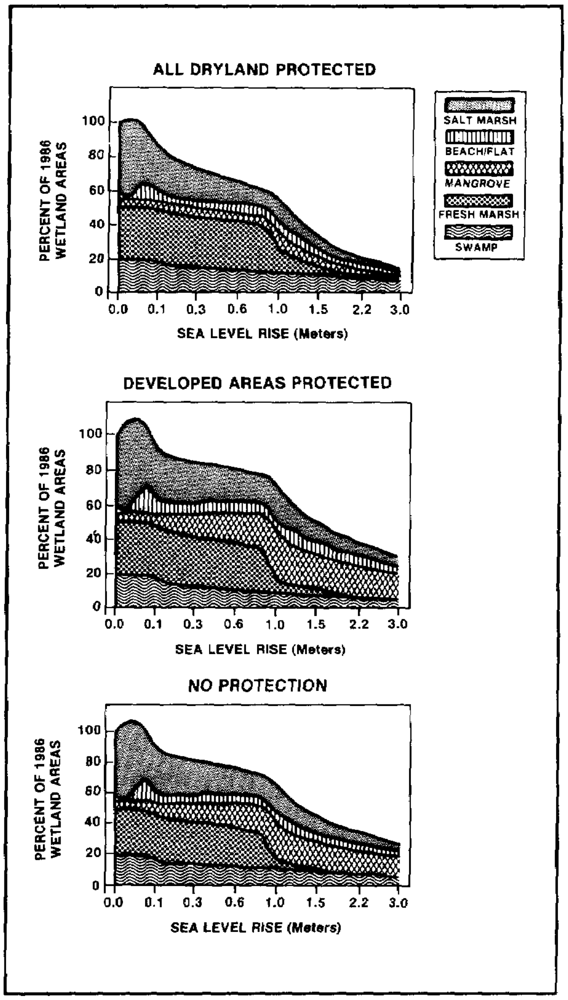

Figure 16-5. Wetlands loss in the Southeast for three shoreline protection options (Park et al., Volume B). (NOTE: These numbers are different from those in Table 16-4 because they include nonvegetated wetlands, i.e., beaches and flats.)

Cost of Protecting Recreational Beaches

In Volume B, Leatherman notes that the projected rise in sea level would threaten all developed recreational beaches. Even a 1-foot sea level rise would erode shorelines over 100 feet throughout the Southeast. Along the coasts of North Carolina and Louisiana, the erosion would be considerably greater. Because the distance from the high tide line to the first building is rarely more than 100 feet, most recreational beaches would be lost, unless either the buildings were removed or coastal protection measures were undertaken.

Table 16-4 illustrates Leatherman's estimates of the cost of protecting recreational beaches by pumping sand from offshore locations. (See Table 7-3 for state-by-state results). A 1-meter rise in sea level could imply almost $20 billion in dredging costs, with Texas spending $8.5 billion and Florida and Louisiana each spending over $3 billion.

Using constant unit costs (except for Florida), Leatherman estimated that a 2-meter rise could only double the total cost to $43 billion. Titus and Greene estimated that if the unit costs of sand increased, 1- and 2-meter rises could cost $30 and $74 billion, respectively. They also estimated that the respective costs of rebuilding roads and utilities on barrier islands could be $5 to 9 billion, $10 to 40 billion, and $60 to 75 billion for the three scenarios.

Cost of Protecting Calm-Water Shorelines

While Leatherman focused only on the open ocean coast, Weggel et al. estimated the regionwide costs of holding back the sea in developed sheltered and calm-water areas. Weggel et al. estimate that about $2 billion would be spent to raise roads and to move structures, and $23 billion would be spent to erect the necessary levees and bulkheads for a 2meter rise. Table 16-4 shows confidence intervals estimated by Titus and Greene, which imply a total cost of $42 to 75 billion for a 1- meter rise. The combined cost is $68 to 83 billion. These estimates do not include the costs of preventing flooding or of protecting water supplies.

Table 16-4. Summary of Results of Sea Level Rise Studies for the Southeast (billions of dollars)

Response	Baseline	50-cm rise	100-cm rise	200-cm rise
Developed areas are protected				
Land lost				
Dryland lost (mi^2)	1,300-3,700	1,900-5,500	2,600-6,900	4,200-10,100
Wetlands lost (%)[a]	11-22	24-50	34-77	40-90
Cost of coastal defense		19-28	42-75	127-174
Open coast				
Sand	3	10-15	19-30	44-74
Elevated structures	negligible[b]	5-9	10-40	60-75
Sheltered shores	negligible[b]	2-5	5-13	9-41
All shores are protected				
Land lost				
Dryland lost (mi^2)				
Wetlands lost (%)[a]	0	0	0	0
No shores are protected	0	38-61	47-90	68-93
Land lost				
Dryland lost (mi^2)	N/A	2,300-5,900	3,200-7,600	4,800-10,800
Wetlands lost (%)[a]	N/A	22-48	30-75	37-88

[a] "Wetlands" refers to vegetated wetlands only; it does not include beaches or tidal waves.
[b] Costs due to sea level rise are negligible.
Source: Titus and Greene (Volume B).

Tennessee Valley Authority Studies

The Tennessee Valley Authority (TVA) was created in 1933 to spur economic growth in an area previously considered to be one of the nation's poorest. Geographically isolated by the Appalachian Mountains, the region lacked electricity and roads, and the Tennessee River could not provide reliable transportation because it flooded in the spring and dried to a trickle during the summer. By creating the TVA, Congress sought to remedy this situation by harnessing the river to provide electricity, to prevent the flooding that had plagued Chattanooga, and to ensure sufficiently stable riverflows that would permit maintenance of a 9-foot-deep navigation channel.

The region administered by the TVA covers 40,000 square miles and includes parts of seven states. In the last half century, the TVA has coordinated the construction of 43 major dams along the river and its tributaries, many of which are shown in Figure 16-6. The system provides power to over 7 million people and contains 675 miles of navigable waterways with annual commercial freight of 28 million tons. The lakes created by the dams have over 10,000 miles of shorelines, which generate 75 million visits each year and along which people have invested $630 million, boosting the region's annual economy by $400 million (Miller and Brock, Volume A).

To assess the potential impacts of climate change, Miller and Brock conducted a modeling study of the water resource implications, and Meo et al. examined the policy implications for the TVA.

TVA Modeling Study

Methods

Miller and Brock used the TVA's "Weekly Scheduling Model," which the Agency currently uses in setting the guidelines for its operations, to assess the impacts of climate change. This linear programming model selects a weekly schedule for managing each reservoir in the TVA system by sequentially satisfying the objectives of flood control, navigation, water supply, power generation, water quality, and recreation. Miller and Brock used this model to simulate reservoir levels, riverflows, and hydropower generation for wet and dry scenarios, derived from the runoff estimates from the GISS doubled CO_2 model run.

TVA was unable to use a hydrologic model to estimate runoff for this study. Instead, they sought to use the runoff estimates from general circulation models. Unfortunately, the OSU and GFDL models estimate that there is no runoff today, which would not permit derivation of a scenario. Therefore, the GISS runoff estimates were used as the "wet scenarios." Based on Rind (1988), the dry scenario simply assumed that the change in runoff would be the inverse of the change assumed in the wet scenario. Therefore, a TVA study should be viewed as an assessment of the system's sensitivity to climate change, not as the literal implications of particular general circulation models.

Miller and Brock assessed the potential impacts of climate change on flood levels in Chattanooga, Tennessee, using a model that had been developed to estimate the constraints on weekly tributary releases. They also estimated the potential implications for water quality in the Upper Holston Basin of the valley, using a reservoir water quality model, a riverflow model, and a water quality model that TVA has used in the past to determine the environmental constraints affecting riverflow.

Limitations

Because the riverflow scenarios were not based on hydrologic analysis, conclusions cannot be drawn regarding the sensitivity of riverflow to climate change; a more thorough study should apply a basinwide hydrologic model to the region. A key limitation for the flood analysis was that EPA assumed that every storm in a given month would result in a change in riverflow proportional to the change in monthly runoff rather than incorporating potential changes in flood frequency and intensity. (For climate change scenarios, see Chapter 4: Methodology.) Finally, the study assumed that TVA would not mitigate impacts by changing its operating rules for the reservoirs in response to climate change.

Results

Reservoir levels

Figure 16-7 shows the estimates of the changes in reservoir levels in the Norris Reservoir for the wet and dry scenarios. Currently, water levels are typically

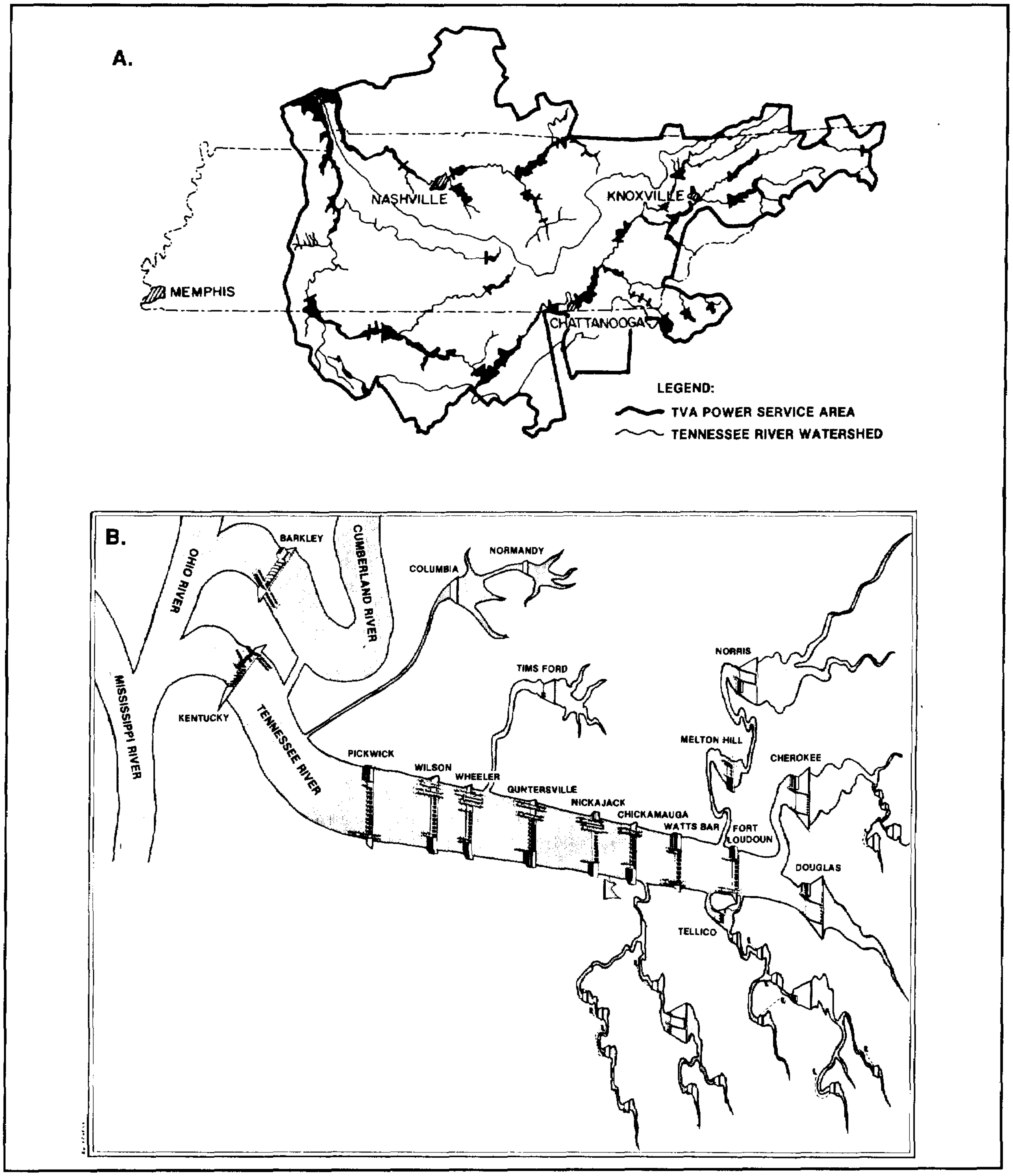

Figure 16-6. (A) Map of the TVA region, and (B) schematic of the TVA reservoir system (Miller and Brock, Volume A).

above 1,010 feet (NGVD) from early May to early August. Under the wet scenario, the water would generally be above this level from early April to early September; during the driest years (1%), the water levels would be similar to the current normal level between May and October. In the dry scenario, water levels would never exceed 1,005 feet in a typical year, and even during the wettest years (1%) they would barely exceed the current normal condition between April and September.

Changes in lake levels of this magnitude would have important implications for recreation in the Tennessee Valley, which is supported by facilities worth over $600 million. Even today, recreation proponents are concerned with reservoir levels dropping during some summers. Miller and Brock found that the wet scenario would largely eliminate current problems with low lake levels; in contrast, the dry scenario would make these problems the norm.

Water Quality

Miller and Brock found that a drier climate could also create environmental problems. Lower flows would reduce the dilution of municipal and industrial effluents discharged into the river and its tributaries. Moreover, because water would generally remain at the bottom of reservoirs for a longer period of time, the amount of dissolved oxygen could decline; this would directly harm fish and reduce the ability of streams to assimilate wastes. Miller and Brock concluded that the water supplies from TVA would probably be sufficient, but that TVA could experience operational difficulties and customer dissatisfaction due to degraded water quality. During extended low-flow conditions, wastes would have increased opportunities to backflow upstream to water supply intakes.

Flooding

Although a drier climate could exacerbate many current problems facing TVA, a wetter climate could create difficulties, particularly the risk of flooding, in matters that are currently under control. Miller and Brock found that in the wet scenario, during exceptionally wet years, storage would be inadequate at the tributary reservoirs; this condition could result in uncontrolled spillage over dams. A high probability of flooding would also exist at Chattanooga. Miller and Brock examined the levels of the five worst floods of the last 50 years at Chattanooga, which did not overflow the banks of the Tennessee River or flood the city. However, under the wet scenario, two of the floods would overtop the banks. The worst flood could reach a level of 56.3 feet and cause over $1 billion in damages; the second worst could reach a level of 46 feet and cause over $200 million in damages (see Figure 16-8).

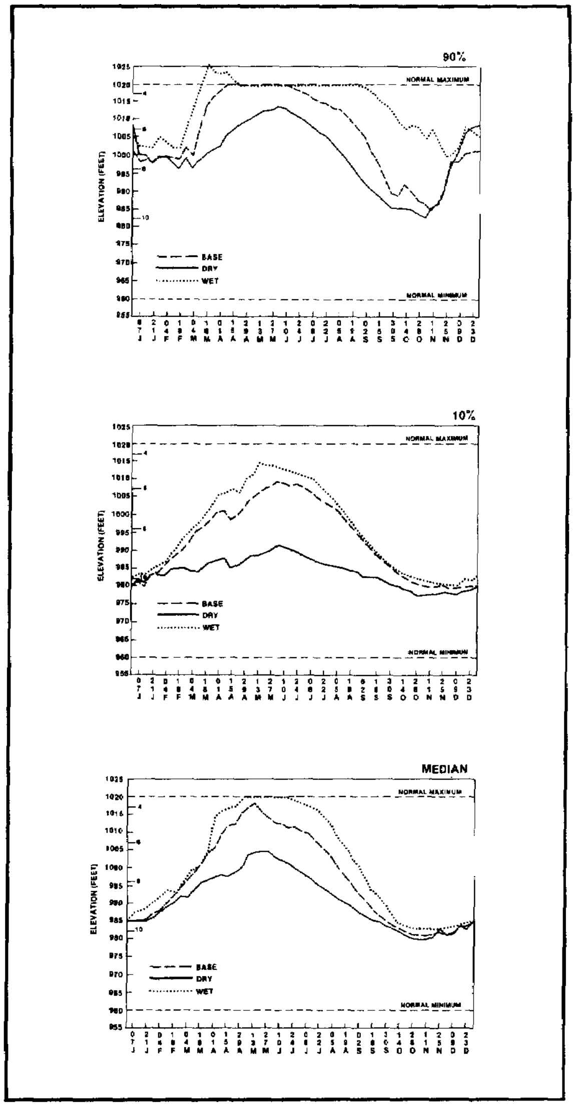

Figure 16-7. Water levels in Norris Reservoir under climate scenarios: (A) 10% wet test years; (B) median; and (C) 10% driest years (adapted from Miller and Brock, Volume A).

Flooding could be reduced if operating rules were modified to keep water levels lower in reservoirs on tributaries (although this would diminish the hydropower benefits from a wetter climate). However, changes in operating rules would not be sufficient to protect Chattanooga from being flooded during a repeat of the worst storm, because rainfall would be largely concentrated over the "mainstem" reservoirs, which do not have substantial flood-control storage.

Power Generation

Miller and Brock calculated that the wet and dry scenarios imply, respectively, an annual increase of 3.2megawatt-hours (16%, $54 million per year) and a decrease of 4.6 megawatt-hours (24%, $87 million per year), given current capacity and operating rules.

Climate change could also have an impact on fossil-fuel powerplants. If river temperatures become warmer, they will require additional dilution water. Although sufficient water would be available if the climate became wetter, meeting minimum flow requirements would be more difficult if climate became drier. Miller suggested that the most feasible operational change would be to cut back power generation at fossil-fuel powerplants during periods of low flow. However, hydropower production would also be reduced during periods of low flow, so cutting back production might not be acceptable. One alternative would be to construct cooling towers, which would eliminate discharges of hot water, at a capital cost of approximately $75 million.

Tennessee Valley Policy Study

Meo et al. (Volume J) analyzed the history, statutory authority, and institutional structure of the TVA to assess the ability of the organization to respond to climate change. Their analysis relied both on the available literature and on interviews with a few dozen officials of TVA and states within the region. They divided the possible responses of TVA into two broad categories: (1) continuing the current policy of maximizing the value of hydroelectric power, subject to the constraints of flood control and navigation; and (2) modifying priorities so that power generation would be subordinated to other objectives if doing so would yield a greater benefit to the region. They concluded that if the climate became wetter, current policies would probably be adequate to address climate change because the only adverse effect would be the risk of additional flooding, which is already a top priority of the system.

If climate became drier, on the other hand, existing policies might be inadequate, because they require power generation to take precedence over many of the resources that would be hardest hit. Although they expect that the TVA will be more successful at addressing future droughts, Meo et al. found that during the 1985-86 drought, falling lake levels impaired recreation and reduced hydropower generation, forcing the region to import power while five powerplants sat idle. Meo et al. point out that groundwater tables are falling in parts of the region, in part because numerous tributaries recharge the aquifers whenever water is flowing but are allowed to run dry when water is not being released for hydropower. They suggest that even without climate change, the deteriorating groundwater quality and availability are likely to lead a number of communities to shift to surface water supplies in the coming decades, adding another use that must compete for the water that is left over when the demands for power have been met. Even with current climate, they contend, the TVA should assess whether other uses of the region's water resources would benefit the economy more. If climate becomes drier, the need for such a reevaluation will be even more necessary.

Studies of the Impacts on Lake Lanier and Apalachicola Bay

Figure 16-9 shows the boundaries of the 19,800-square-mile Chattahoochee- Flint Apalachicola River Basin. The U.S. Army Corps of Engineers and others who manage the Chattahoochee River as it passes through Lake Lamer on its way to the Apalachicola estuary and the Gulf of Mexico face many of the same issues as those faced by the TVA. However, they also are managing the water supply of Atlanta, the second largest city in the Southeast, and the flow of water into an estuary that supports the most productive fishery in Florida (U.S. Department of Commerce, 1988).

A number of researchers were involved in EPA's assessment of the potential implications of climate change for this watershed. A study of Lake Lamer and a study of the implications for the fish in Apalachicola Bay are discussed in the following sections of this chapter.

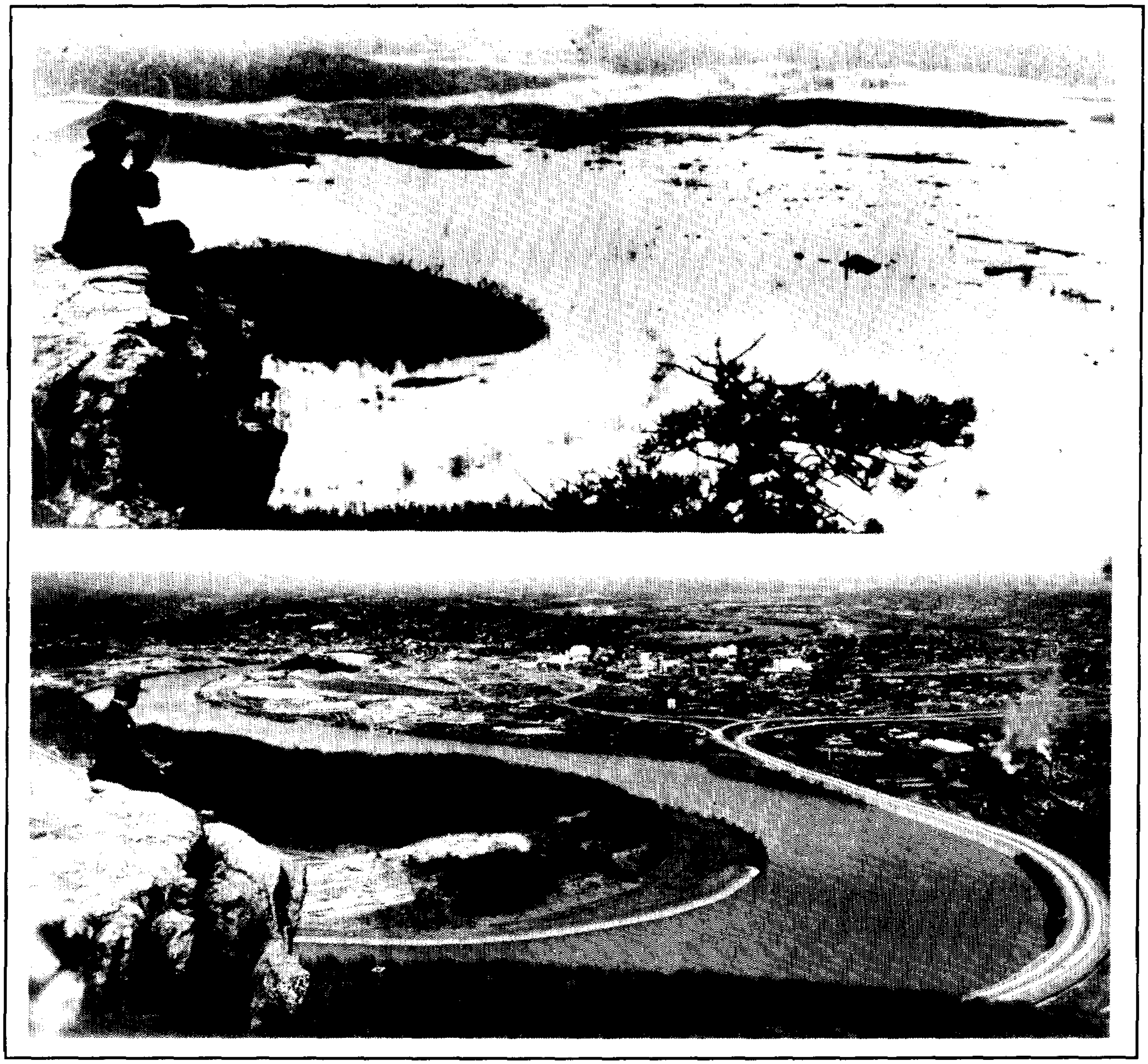

Figure 16-8. Chattanooga was vulnerable to flooding until the TVA system of dams was constructed. The upper photo shows the 1867 Flood, with water levels similar to those projected by the Miller and Brock under the wet scenario (Miller and Brock, Volume A).

Lake Lanier

Lake Lanier, located 30 miles northeast of Atlanta, is a source of water for the city and nearby jurisdictions. Federal statutes require the U.S. Army Corps of Engineers to manage Lake Lanier to provide flood control, navigation, and hydropower. Nevertheless, the lake is also managed to meet nonstatutory objections such as recreation, minimum flows for environmental dilution, and water supply.

Since Lake Lanier was dammed in 1957, the statutory objectives of flooding and navigation have been met; annual hydropower generation has been 134

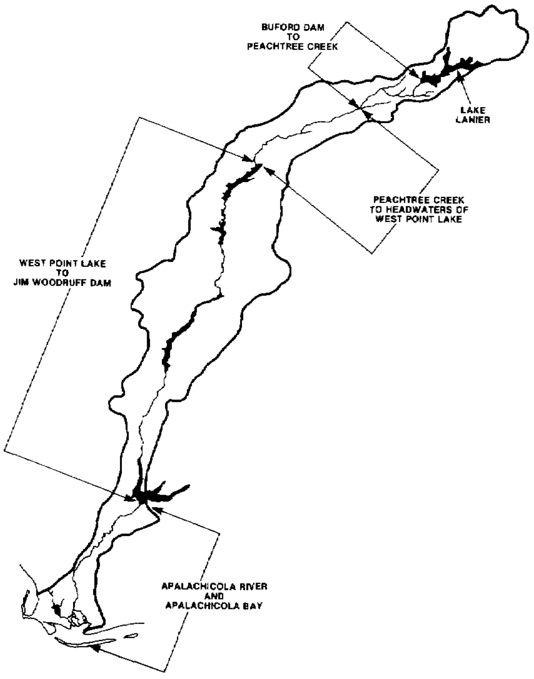

Figure 16-9. Drainage area of the Apalachicola-Chattahoochee-Flint River system.

MWH[3], equal to 2% of today's power requirements for Atlanta; and the releases of water have fulfilled the additional minimum flow needed to dilute the effluents from sewage treatment plants.

During the last two decades, the lake's shoreline has been substantially developed with marinas, houses, and hotels. To a large degree, the residents have become accustomed to the higher water levels that prevailed from the 1970s through 1984. Droughts from 1985 to the present, however, have lowered lake levels, disrupting recreation. In the summer of 1986, navigation for recreational boats located downstream of the lake was curtailed because of minimal releases from the lake. In 1988, Atlanta imposed water-use restrictions, with the objective of cutting consumption by 10 to 20%. A bill has been introduced to add recreation to the list of statutory purposes (HR-4257).

Runoff in the Chattahoochee River Basin

Study Design. Hains estimated runoff in the Chattahoochee River Basin and the flow of water into Lake Lanier for the three scenarios. He calibrated the Sacramento hydrology model developed by the National Weather Service (Burnash et al., 1973) to the conditions found in the watershed of the upper Chattahoochee River. He then generated scenarios of riverflow for the baseline climate and the GCM scenarios.

Limitations. The Sacramento model was designed primarily for flood forecasting, not base flow. In addition, the model was calibrated using the data on evaporation of water from pans, which is not perfectly correlated with evapotranspiration, and these data came from a nearby watershed.

Since the analysis was based on scenarios of average monthly change, it did not consider potential changes in variability of events such as floods. The analysis did not incorporate changes in vegetation, which could affect runoff.

Results. As with the Tennessee River, the major climate models disagree on whether the Chattahoochee watershed would become wetter or drier with an effective doubling of greenhouse gases. Hains estimated that under the wetter GISS scenario, the average annual riverflow of the Chattahoochee River would increase by 13%; the drier OSU and GFDL models imply declines of 19 and 27%, respectively, as shown in Figure 16-10. The GISS scenario implies slight decreases in winter flow and increases the rest of the year. Under the GFDL scenario, these substantial decreases were estimated throughout the year, with almost no flow in late summer. The OSU scenario also shows reductions, but the reduction is greatest during the flood season (February to May) and negligible

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[3] Personal communication from Harold Jones, Systems Engineer, Southeast Power Administration, Department of Energy, September 12, 1988.

during the dry season (late summer/early fall).

Management of Lake Lanier

Study Design. Sheer and Randall (Volume A) examined the implications for water management of the riverflow changes estimated by Hains. They modified a monthly water balance model/operations model previously applied in southern California for the lake, based on current operating rules for the reservoir. For the first set of runs, the model assumes that (1) minimum flows are maintained for navigation and environmental dilution at all times, (2) lake levels are kept low enough to prevent flooding, (3) historic rates of consumption continue, and (4) peak hydropower generation is maximized. To ensure that the assumptions adequately reflect the actual decision rules used by water managers, Sheer and Randall reviewed the rules with local officials from the U.S. Army Corps of Engineers, the Atlanta Regional Council, and others responsible for managing the water supply. In a second set of runs, they examined the impacts of climate change under alternative operating rules that assume recreation is also a statutory objective.

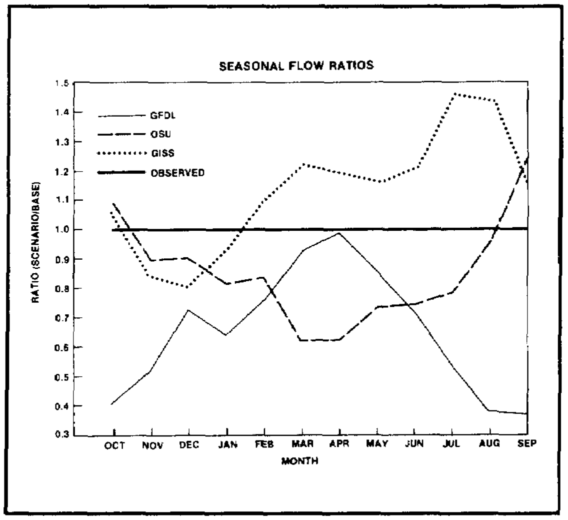


Figure 16-10. Ratios of flow under doubled CO_2 scenarios to base case in Upper Chattahoochee River.

Limitations. Sheer and Randall did not consider changes in demand for water due to climate change or population growth; thus, it produces high estimates of future water availability under all scenarios. Moreover, the results were not compared with historic lake levels.

Results. Figure 16-11 shows the Sheer and Randall estimates of lake levels; Figure 16-12 shows quarterly hydropower production. Under the relatively wet GISS scenario, annual power production could increase by 9%. The higher streamflows in this scenario would still be well below those that occasionally occurred before Lake Lamer was closed; hence, no significant threat of flooding would exist for a repeat of the climate of 1951-80. Under the relatively dry GFDL scenario, however, power production could drop 47%, and lake levels would be likely to drop enough to substantially disrupt recreation. This scenario assumes that Atlanta would continue to take as much water as it does currently (allowing for growth would increase water supply problems).

Sheer and Randall also examined the implications of making recreation a statutory objective. Although it would be possible to maintain lake levels, Atlanta's water supply would be threatened. With the current climate, strict enforcement of such a policy would result in Lake Lanier supplying no water to metropolitan Atlanta for 8 months of every 30 years. Although under the GISS scenario this would be reduced to 1 month, under the dry GFDL scenario, Atlanta would have to use an alternative source of water 1 to 3 months each summer.

Implications. Climate change combined with population growth may require water managers to reexamine the tradeoffs between the various uses of the Chattahoochee River and Lake Lanier. A number of local water officials who met with Sheer suggested that an appropriate response to changing water availability might be to relax minimum flow requirements for navigation and environmental quality. They reasoned that minimum flows for environmental purposes are based on the assumption that sewage treatment plants are discharging at their maximum rates and that temperatures are high, conditions that are usually not met. They also argued that little is accomplished by maintaining minimum flows for navigation because ship traffic is light in the lower Chattahoochee. Others argued, however, that it would be unwise to assume that minimum flows could be decreased because future growth may increase the need for dilution of effluents, and warmer temperatures would speed biological activity. The likely impacts of climate change on Apalachicola Bay may also increase the need to

Figure 16-11. Lake Lanier elevation (September) under doubled CO_2 scenarios (Sheer and Randall, Volume A).

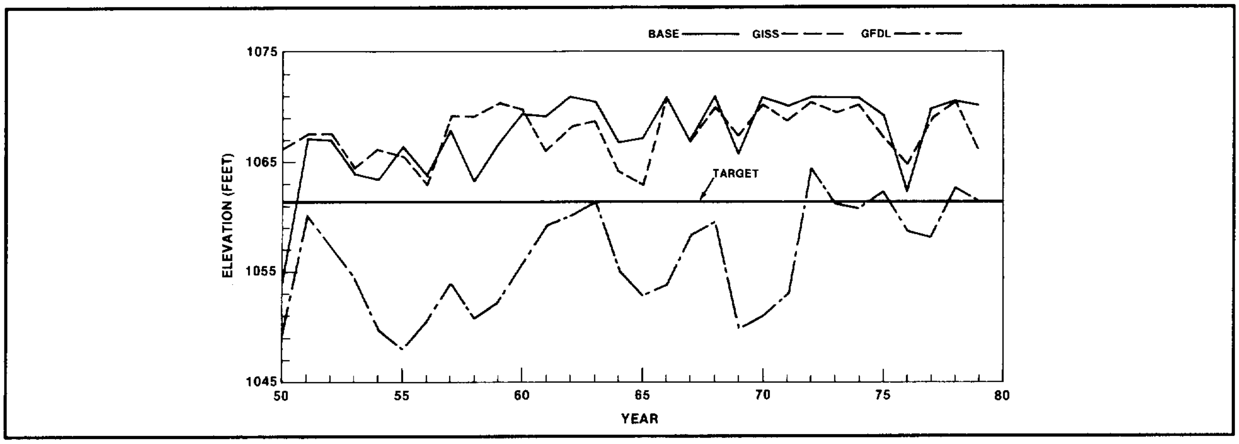
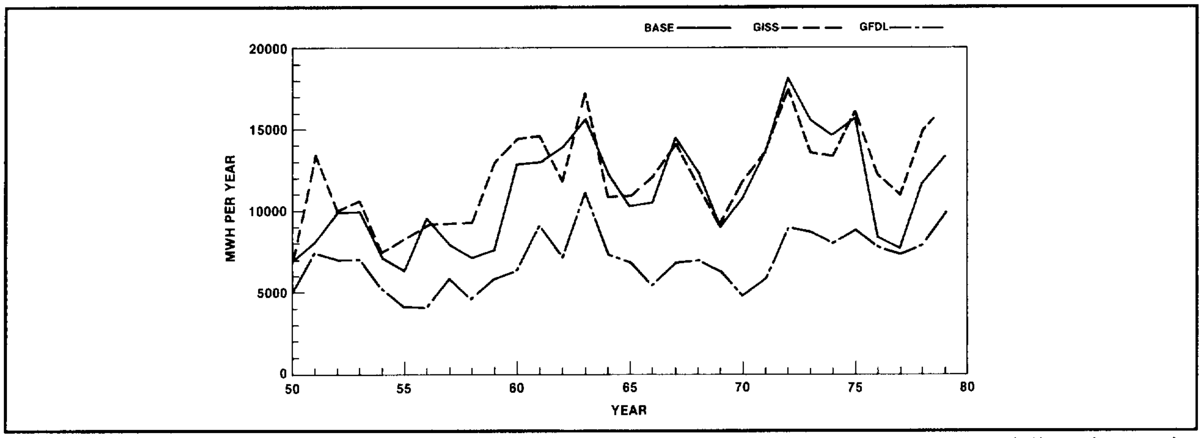


Figure 16-12. Lake Lanier power generation under doubled CO_2 scenarios (Sheer and Randall, Volume A).



maintain minimum flows.

Apalachicola Bay

Apalachicola Bay supports hundreds of commercial fishermen; over 80% of Franklin County earns a livelihood from the bay (Meo et al. Volume J). The contribution of fishing to the area was estimated at $20 million for 1980, representing 90% of Florida's oyster harvest and 10% of its shrimp harvest. This figure is projected to grow to $30 to $60 million by 2000.

Although the state has purchased most of the land that is not part of a commercial forest, economic pressures on forestry companies to sell land for coastal development are increasing. In 1979, the National Oceanic and Atmospheric Administration created the Apalachicola National Estuarine Sanctuary to prevent development from encroaching into this relatively pristine estuarine environment.

The biology of the Apalachicola Bay estuary may be affected by higher temperatures, higher sea levels, and different flows of water into the Apalachicola River. Hains estimated the flow of the Apalachicola River, and Park et al. estimated wetland loss due to sea level rise. Livingston used both of these results and the temperature change scenarios to evaluate the potential impacts on the bay's fish populations.

Sea Level Rise

The methods of Park et al. for estimating wetland loss are described in Chapter 7: Sea Level Rise.

They estimated that a 1-meter rise in sea level would inundate approximately 60% of the salt marshes in Apalachicola Bay, and that mangrove swamps, which are rarely found outside southern Florida today, would replace the remaining salt marsh. Table 16-5 illustrates their estimates.

Apalachicola Riverflow

Study Design. Hains estimated the impact of climate change on riverflow, using a regression model, which is simpler than the Sacramento model he used for the Chattahoochee River analysis. The regression expressed the logarithm of riverflow as a function of the logarithms of precipitation and evapotranspiration for a few weather stations located in the basin.

Limitations. Hains' procedure greatly oversimplified the relationships between the causal variables and riverflow, ignoring the impacts of reservoir releases and the failure of the relationships to fit the simple log-linear form. These results should be interpreted as an indication of the potential direction of change.

Results. Figure 16-13 illustrates Hains' estimates of average monthly flows for the Apalachicola estuary. Annual riverflow would decrease under all scenarios, although it would increase in the summer and fall for the GISS and OSU scenarios, respectively.

Figure 16-13. Doubled CO_2 flow into Apalachicola Bay (Hams, Volume A).

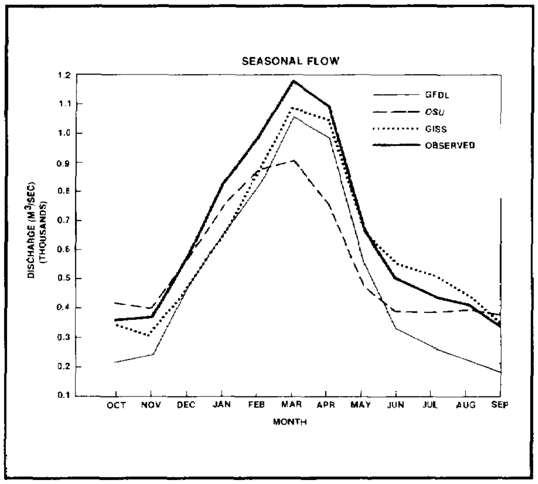


Table 16-5. Remaining Coastal Wetlands in Apalachicola Bay in the Year 2100 (hectares)

Area	1987	Current area sea level rise	50-cm rise	100-cm rise	200-cm rise
Swamps	9.46	6.71	6.26	5.47	4.16
Fresh marsh	1.46	1.27	1.17	1.00	0.25
High marsh	1.19	0.37	0.04	0.04	0.02
Low marsh	3.42	2.33	0.39	0.06	0.03
Mangrove	0	0	3.06	2.13	1.80
Total wetlands	15.53	10.68	10.92	8.70	6.26

Source: Park et al. (Volume B).

Fish Populations in Apalachicola Bay

Study Design. Using data from the literature on the tolerance of various species to warmer temperatures, Livingston estimated the number of months in a typical 30-year period during which the estuary would be too hot for these species and extrapolated this information to estimate reductions in populations.

Hydrologic modeling was not used to estimate the combined impacts of sea level rise and changing riverflow on salinity. Instead Livingston used historic data to estimate regression equations relating riverflow to salinity and salinity to populations of some commercially important seafood species.

Limitations. There is no historical record by which to estimate the impact of warmer temperatures on the Apalachicola (or any other) estuary. Livingston did not model the relationships between various aquatic species or how they would change. He did not consider how fmfish and shellfish might adapt to climate change, and he was unable to estimate the impact of wetland loss on populations of finish and shellfish.

The limitations in Hains' estimates of riverflow do not significantly affect the results of Livingston's study because riverflow was only one of several variables to be considered. The uncertainties surrounding changes in rainfall probably dwarf any errors due to Hains' simplified hydrology, and higher temperatures and sea level rise appear to be more important.

Results. The results of this study suggest a dramatic transformation of the estuary from subtropical to tropical conditions.

Warmer temperatures. Livingston concluded that warmer temperatures would have a profound effect on seafood species in the estuary because many species cannot tolerate temperatures much above those that currently prevail. Figure 16-14 compares the number of months in a 6-year period (based on 1971-76) in which temperatures exceed a particular level for the current climate and the GISS and GFDL scenarios, with known thresholds for major commercial species.

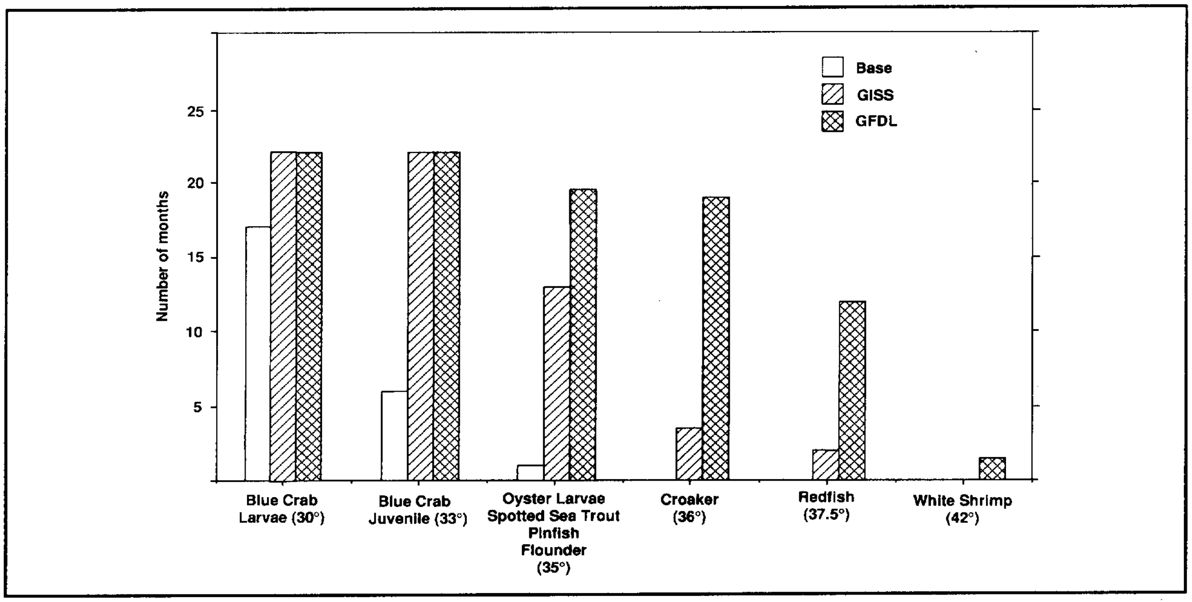


Figure 16-14. Months in a 6-year period during which temperatures (°C) would be too high for selected species under doubled $_{CO_2}$ scenarios (Livingston, Volume E).

Livingston concluded that crabs, shrimp, oysters, and flounder could not survive in the estuary with the warming estimated in the GISS and GFDL scenarios, which imply close to 100% mortality for blue crab larvae and juveniles. The GFDL scenario could cause over 90% mortality for spotted sea trout, oyster larvae, panfish, and flounder. The mortality under the milder GISS scenario would be only 60%.

Although Livingston concludes that the oysters would probably be eliminated, he cautions that shrimp and other mobile species might adapt by fleeing the estuary for cooler gulf waters during the summer. However, such a flight would leave them vulnerable to predators.

Increased salinity. Although sea level rise and warmer temperatures seem likely to substantially reduce the productivity of the estuary, the probable impact of precipitation changes is less clear. If riverflow in the Chattahoochee declines, it would combine with sea level rise to increase salinity concentrations in the estuary. Livingston concluded that oysters are the most vulnerable to increases in salinity because oyster drill and other predators, as well as the disease MSX, generally require high salinities. Livingston estimated losses of 10 to 35% for oysters, blue crabs, finfish, and white shrimp under the GFDL scenario because of salinity increases alone.

Sea level rise. Livingston also concluded that the loss of wetland acreage would have important impacts on the estuary. Table 16-6 shows Livingston's estimates of losses in particulate organic carbon, the basic source of food for fish in the estuary. Sea level rise between 50 and 200 centimeters would reduce available food by 42 to 78%. A proportionate loss in seafood populations would not necessarily occur, since organic carbon food supplies are not currently the constraining factor for estuarine populations. However, wetlands also are important to larvae and small shrimp, crabs, and other species, serving as a refuge from predators. A rise in sea level of a meter or more could lead to a major loss of fisheries.

Despite the adverse impacts on shellfish and flounder, a number of species might benefit from global warming. For example, Livingston points out that pink shrimp could become more prevalent. Moreover, some finfish spend their winters in Apalachicola Bay and occasionally find the estuary too cold. Other species such as rock lobster that generally find the waters too cold at present may also be found in the estuary in the future.

Implications. Based on Livingston's projections, Meo et al. (Volume J) used current retail prices of fish to estimate that the annual net economic loss to Franklin County could be $5 to $15 million under the GFDL scenario, $1 to $4 million under GISS, and $4 to $12 million under the OSU scenario.

Livingston's results should not be interpreted to mean that fishing will be eliminated from Apalachicola Bay. The extent to which commercially viable tropical species could replace the species that are lost was not estimated.

Table 16-6. Projected Changes of the Net Input of Organic Carbon (metric tons per year) to the Apalachicola Bay System for Various Scenarios of Sea Level Rise

Factor	Fresh wetlands	Seagrass	Salt marshes	Phytoplankton	Total
Current scenario for 2100	30,000	27,200	46,905	233,280	337,385
Baseline sea level rise	26,100	28,700	23,500	144,640	222,940
0.5-meter rise	24,000	28,800	4,690	71,450	128,940
1.0-meter rise	21,300	30,100	940	58,790	111,130
2.0-meter rise	4,980	31,035	780	15,160	51,955

Source: Livingston (Volume E).

Agriculture

Agriculture in the Southeast will be affected directly by changes in climate and indirectly by changes in economic conditions and pests. This section presents results from a crop modeling study of yield changes by Peart et al., and regional results from national studies of agricultural production shifts by Adams et al. (Volume C) and of impacts of changes in pest populations by Stinner et al. (Volume C).

Crop Modeling Study

Study Design

Peart et al. (Volume C) used the crop models CERES-Maize (Jones and Kiniry, 1986) and SOYGRO (Wilkerson et al., 1985) to estimate the impacts of climate change on yields of corn and soybeans for 19 sites throughout the Southeast and adjacent states. Agricultural scientists have used these models for several years to project the impacts of short-term climatic variations. They incorporate the responses of crops to solar radiation, temperature, precipitation, and soil type, and they have been validated over a large range of climate and soil conditions in the United States and other countries.

The major variable not considered by these and other existing agricultural models is the direct "fertilization effect" of increased levels of atmospheric carbon dioxide. Peart et al., therefore, modified their models to consider both the increased rate of photosynthesis and the increased water-use efficiency that corn and soybeans have exhibited in field experiments (see Chapter 6: Agriculture).

Limitations

The analysis of combined effects is new research and will need further development and refinement. The model runs use simple parameters for CO effects, assume higher atmospheric concentration of CO 2 than are predicted, and probably overestimate the beneficial impact on crop yields. The direct effects of CO_2 in the crop modeling study results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases, such as methane, also are increasing, the equivalent warming of a doubled CO 2 climate may occur somewhat before an actual doubling of atmospheric CO_2. A level of 660 ppm CO_2 . was assumed for the crop modeling experiments, while the CO_2 concentration in 2060 is estimated to be SSS ppm Hansen et al., 1988) (see Chapter 6: Agriculture).

The study assumed that soils were relatively favorable for crops, with low salinity or compaction, and assumed no limits on the supply of all nutrients, except nitrogen. The analysis considers neither change in technology nor adverse impacts due to changes in storm frequency, droughts, and pests and pathogens.

Results

Soybean Yields. Table 16-7 illustrates the results of the soybean model for 13 nonirrigated sites in the study area, as well as Lynchburg, Virginia, a colder site included for comparison purposes.

The relatively wet GISS and relatively dry GFDL scenarios imply very different impacts on yields. In the GISS scenario, the cooler sites in Georgia and the Carolinas mostly show declines in soybeans yields of 3 to 25%, and the other sites show declines of 20 to 39%, ignoring CO_2 fertilization. When the latter effect is included, the Atlantic Coast States were estimated to experience gains of 11 to 39%, and the other states could vary from a 13% drop in Memphis to a 15% gain in Tallahassee. (Tennessee fares worse than the North Carolina sites at similar latitudes because its grid cell does not receive as favorable an increase in water availability.)

By contrast, the dry GFDL scenario results in very large drops in soybean productivity, with all but one site experiencing declines greater than 50% and eight sites losing over 75%, considering only the impact of climate change. Even when CO_2 fertilization is considered, all but four sites experience losses greater than 50%.

Corn Yields. The two scenarios differ in a similar fashion for nonirrigated corn. However, in the case of irrigated corn, where the analysis primarily reflects the impact of temperature increases, the two scenarios show more agreement. When CO_2 fertilization was not considered, drops of 13 to 20% were estimated

Table 16-7. Impacts of Doubled CO_2 Climate Change on Soybean Yields for Selected Southeastern Sites for Climate Change Alone and for Climate Change and CO_2 Fertilization (percentage change in yield)[a]

Site	Climate change only		Climate change and CO_2 fertilization	
	GISS	GFDL	GISS	GFDL
Memphis, TN	-38	-88	-13	-70
Nashville, TN	-30	-52	+4	-81
Charlotte, NC	-7	-92	+32	-88
Raleigh, NC	-3	-87	+39	-76
Columbia, SC	-20	-78	+18	-62
Wilmington, NC	-11	-62	+25	-41
Atlanta, GA	-11	-78	+27	-67
Macon, GA	-25	-91	+11	-82
Tallahassee, FL	-20	-51	+15	-17
Birmingham, AL	-31	-54	0	-29
Mobile, AL	-34	-43	-8	error
Montgomery, AL	-39	-84	-10	-68
Meridian, MS	-37	-78	-9	-66
Lynchburg, VA	+1	-74	+49	-55

[a] The impacts of Cow fertilization cannot be quantified as accurately as climate change only. The climates shown here overstate the beneficial impact of CO_2 because Peart et al. assume that CO_2 has doubled. Because other gases contribute to the global warming, CO_2 will have increased by a smaller fraction.

[b] Peart et al. investigated the cumber of sites in states adjacent to the Southeast. Lynchburg is included to permit comparison of results for the Southeast with a colder site.

Source: Peart et al. (Volume C).

in the GISS scenario, and drops of 20 to 35% were calculated for the GFDL scenario. When CO_2 fertilization was included, the GISS scenario implied declines of less than 8% for all sites, and the GFDL model showed similar declines for two sites and respective declines of 17 and 27% for Charlotte, North Carolina, and Macon, Georgia.

Irrigation. The two scenarios show more agreement for agricultural fields that are already irrigated. Since the changes in water availability are irrelevant here, the impacts are dominated by the increased frequency of very hot days.

The results are mixed on whether currently dry land areas would be shifted to irrigation. Table 16-8 shows the percentage increases in yields that would result from adding irrigation for particular scenarios. All but four sites could increase yields today by 50 to 75% by irrigating. Under the wetter GISS scenario, irrigation would increase yields only 7 to 53% (compared with not irrigating under the GISS scenario). However, under the dry GFDL scenario, irrigation would increase yields by 50 to 493% -- that is, it would mean the difference between crop failure and a harvest slightly above today's levels in most years. Even without CO_2 fertilization, 75% of the nonirrigated southeastern sites could gain more from irrigation than they would lose from the change in climate resulting from the GFDL scenario.

A farmer's decision to irrigate, shift to other crops, or remove land from production would depend to a large degree on what happens to prices of both crops and water. Even though water is plentiful today, the capital costs of irrigation prevent most farmers in the

Table 16-8. Increases in Corn Yields from a Shift to Irrigation (percent, assuming no CO_2 fertilization)[a]

Site	Current climate	GISS	GFDL
Memphis, TN	70	50	270
Nashville, TN	65	49	205
Charlotte, NC	64	43	486
Raleigh, NC	51	28	444
Columbia, SC	58	47	386
Wilmington, NC	16	8	50
Atlanta, GA	15	7	79
Macon, GA	61	33	489
Birmingham, AL	6	9	61
Mobile, AL	36	41	91
Montgomery, AL	72	39	493
Meridian, MS	62	53	323
Lynchburg, VA	56	37	361

[a] Estimates represent change in yields, given particular scenario, from shifting to irrigation.

[b] Peart et al. investigated a number of sites in states adjacent to the Southeast. Lynchburg is included to permit comparison with Southeast results with those for a colder site.

Source: Column 1 from Peart et al. (Volume C); Columns 2 and 3 derived from Peart et al. and Column 1

Southeast from taking advantage of the potential 50% increases in yields. But if crop failures due to drought became as commonplace as Peart et al. project for the dry GFDL scenario, a major increase in irrigation probably would be necessary. Although groundwater is currently plentiful in the Southeast, no one has assessed whether there would still be enough water if the climate became drier and irrigation increased. Furthermore, climate change may increase the demand for water for nonagricultural uses.

Shifts in Production

Adams et al. (Volume C) examined the impacts of changes in crop yields on farm profitability and cultivated acreage in various regions of the United States. (The methods for this study are discussed in Chapter 6: Agriculture.) Their results suggest that the impact of climate change on southeastern agriculture would not be directly proportional to the impact on crop yields (Table 16-9).

Considering only the impact of climate change, Adams et al. found that the GISS and GFDL scenarios would reduce crop acreage by 10 and 16%, respectively. When CO_2 fertilization is considered, however, Adams et al. project respective declines in farm acreage of 57 and 33% for the GISS and GFDL scenarios. As yields increase, prices decline. Adams et al. estimate that most areas of the nation would lose farm acreage. However, they estimate that the Southeast would experience the worst losses: wlvle the Southeast has only 13% of the cultivated acreage, it would account for 60 to 70% of the nationwide decline in farm acreage. This result is driven by the increased yields that the rest of the nation would experience relative to the Southeast.

When the CO_2 fertilization effect is ignored, the reductions in acreage would be much smaller, although the Southeast would still account for 40 to 75% of the nationwide loss. The general decline in yields would boost prices, which could make it economical for many farmers to irrigate and thereby avoid the large losses associated with a warmer and possibly drier climate.

Agricultural Pests

The modeling and economic studies of agriculture do not consider the impact of pests on crop yields. However, Stinner et al. (Volume C) suggest that global warming would increase the range of several agricultural pests that plague southeastern agriculture. (For details on the methods of this nationwide study, see Chapter 6: Agriculture.) They point out that the northern ranges of potato leafhoppers, sunflower moths, black cutworms, and several other southeastern pests are limited by their inability to survive a cold winter. Thus, milder winters would enable them to move farther north, as illustrated in Figure 16-15. Stinner et al. also note that increased drought frequency could increase the frequency of pest infestations.

Implications of Agriculture Studies

Agriculture appears to be at least as vulnerable to a potential change in climate in the Southeast as in any other section of the country. Unlike many of the

Table 16-9. Impact of Climate Change on Cultivated Acreage in the Southeast' (figures in parentheses are percentage losses)

Region	Baseline	With Direct CO_2		Without Direct CO_2	
		GISS	GFDL	GISS	GFDL
Acreage (millions)					
SE coast	12.5	8.7(30)	7.8(38)	11.5(8)	11.2(10)
Appalachia	15.5	2.8(82)	7.4(52)	14.1(9)	12.9(17)
Delta	19.9	9.3(53)	16.7(16)	17.7(11)	16.2(19)
Total	47.9	20.8(57)	31.9(33)	43.3(10)	40.3(16)

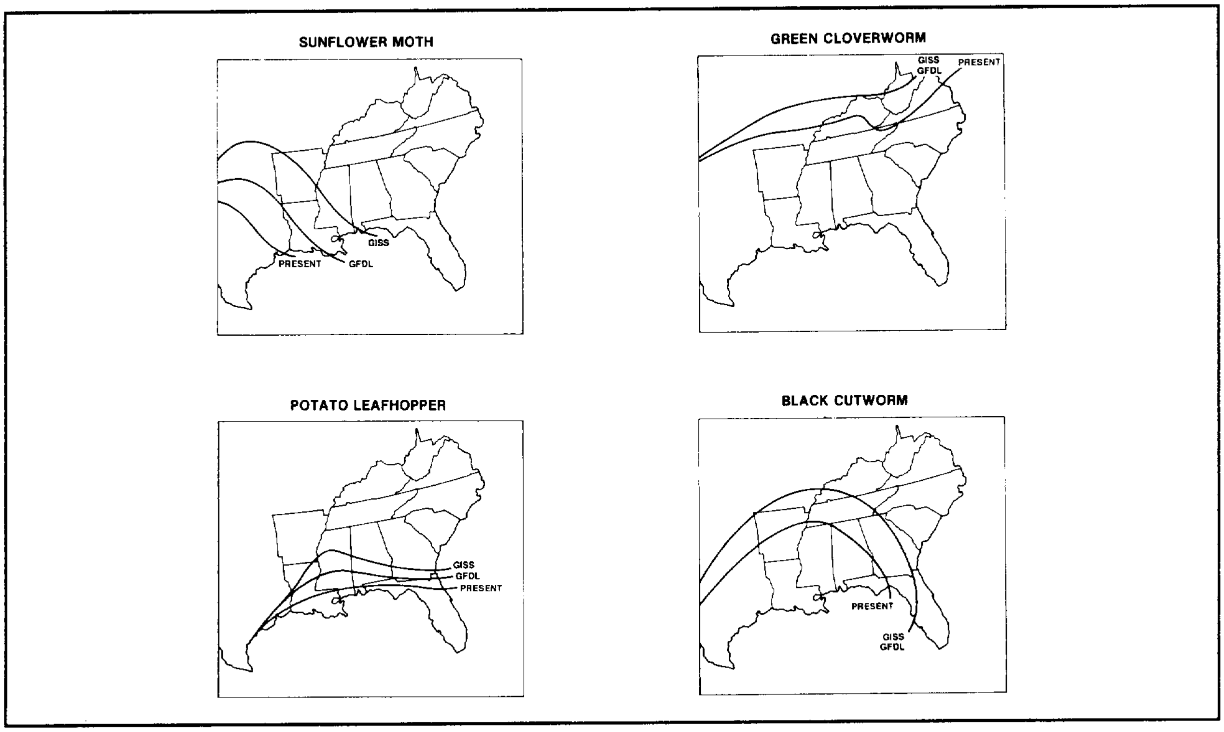


Figure 16-15. Present and predicted northern ranges of various agricultural pests (Stinner et al., Volume C).

colder regions, the benefits of a longer growing season would not appreciably offset the adverse impacts of warmer temperatures in the Southeast, where cold weather generally is not a major constraint to agricultural production.

Florida may present an important exception to the generally unfavorable implications of climate change for crop yields. Although Florida is the warmest state in the Southeast, its agriculture appears to be harmed by cold temperatures more than the agriculture of other states in the region. In recent years, hard freezes have destroyed a large fraction of the citrus harvest several times. As a result, the industry is moving south into areas near the Everglades, and sugarcane, which also thrives in warm temperatures, is expanding into the Everglades themselves. Global warming could enable the citrus and sugarcane areas to include most of the state. Warmer temperatures also would help coffee and other tropical crops that are beginning to gain a foothold in the state. This study, however, did not examine how the frequency of extreme events, such as the number of days below freezing in Florida, would change.

Although Florida's relative abundance of water may make it the exception, the current situation there highlights an important aspect of climate change: Within the context of current prices and crop patterns, the impact of climate change appears to be unfavorable. However, warmer temperatures may present farmers with opportunities to grow different crops whose prices would justify irrigation or whose seasonal cycles would conform more closely to future rainfall patterns.

Forests

Potential Range Shifts

Study Design

Overpeck and Bartlein (Volume D) used two independent methods to study the potential shifts in ranges of forest types over eastern North America. These analyses suggest where trees are likely to grow in equilibrium doubled CO_2 climate conditions after allowing for migration of tree species to fully catch up with climate change. The study only indicates the approximate abundance of different species within a range, not what the transitional effects of climate on forests might be, or how fast trees will be able to migrate to the new ranges. (For a discussion of the study's methodology and limitations, see Chapter 5: Forests.)

Results

Three GCM scenarios and two vegetation models yielded similar results. The abundance of deciduous hardwood populations (e.g., oak), which currently occupy the entire modeled eastern region from the Great Lakes region to the gulf coast, would shift northward away from the gulf coast and almost entirely out of the study region. Because the stand simulation model did not include subtropical species, it was unable to simulate any vegetation along the gulf coast under the very warm doubled CO_2 climate. The results for southern pine were less conclusive but generally show the upper border of the species range moving northward while the southern border remains stable. Growing conditions along the gulf coastal region, however, would also be favorable to subtropical species in a doubled CO_2 environment, but since the models used in the study had no data on such species, it is unclear how southern pine might fare under competition with subtropical varieties.

Transitional Effects

Study Design

Urban and Shugart (Volume D) applied a forest simulation model to a bottomland hardwood forest along the Chattahoochee River in Georgia and to upland sites near Knoxville, Tennessee, Macon, Georgia, Florence, South Carolina, and Vicksburg, Mississippi. Their study considered the OSU, GFDL, and GISS scenarios for doubled CO_2, as well as the GISS transient A scenario through the year 2060.

The model these researchers used was derived from FORET, the "gap" model originally developed by Shugart and West (1977). The model simulates forest dynamics by modeling the growth of each tree in a representative plot of forest land. It keeps track of forest dynamics by assigning each of 45 tree species optimal growth rates, seeding rates, and survival probabilities, and by subsequently adjusting these measures downward to account for less than optimal light availability, temperature, soil moisture, and soil fertility. In the case of the bottomland hardwood site, the model also considers changes in river flooding, based on the flows in the lower Chattahoochee calculated in the Lake Lanier study. The researchers applied the model to both mature forests and the formation of a new forest from bare ground.

Limitations

The results should not be taken literally owing to a number of simplifying assumptions that Urban and Shugart had to make. First, they assumed that certain major species, such as loblolly pine, could not tolerate more than 6,000 (cooling) degree-days per year. These species are not currently found in warmer areas, but the southern limits of their range are also limited by factors other than temperature, such as the Gulf of Mexico and the dry climate of Texas and Mexico. Although the 6,000 degree-day line coincides with these species' southern boundary across Florida, the peculiar environmental conditions of that state make it impossible to confidently attribute an estimate of thermal tolerance to that observation alone. This caveat does not apply to most of the oaks, hickories, and other species found in the cooler areas of the Southeast.

Another important caveat is that the model does not consider the potentially beneficial impact of CO_2 fertilization on photosynthesis, changes in water-use efficiency, or leaf area. Nor did the analysis consider introduction of new species into the region. Thus, there is more confidence about the fate of species currently in the region than about what may replace those species.

Results

The simulations by Urban and Shugart call into question the ability of southeastern forests to be generated from bare ground, particularly if the climate becomes drier as well as warmer. For the Knoxville site, the dry GFDL scenario implies that a forest could not be started from bare ground, while the GISS and OSU doubled CO_2 scenarios estimate reductions in biomass of 10 to 25%. For the South Carolina site, only the GISS climate would support a forest, albeit at less than 50% of today's productivity. The Georgia and Mississippi sites could not generate a forest from bare ground for any of the scenarios. Thus, even with increased rainfall, some sites would have difficulty supporting regeneration.

The transient analyses suggest that mature forests could also be lost -- not merely converted to a different type -- if climate changes. Figure 16-16 shows that none of the forests would decline significantly within 50 years; however, all would decline substantially before the end of the transient run in 80 years. The Mississippi forest would mostly die within 60 years, and the South Carolina and Georgia forests within 80 years. Only the relatively cool Tennessee site would remain somewhat healthy, although biomass would decline 35%.

Although the simulation results suggest that southeastern forests are unlikely to benefit from the global warming, the impact on forests may not be as bad as the model suggests, if new species move in or if loblolly pine can tolerate more than 6,000 degree days per year. Nevertheless, major shifts in forest types are almost certain to occur from the warmer temperatures alone.

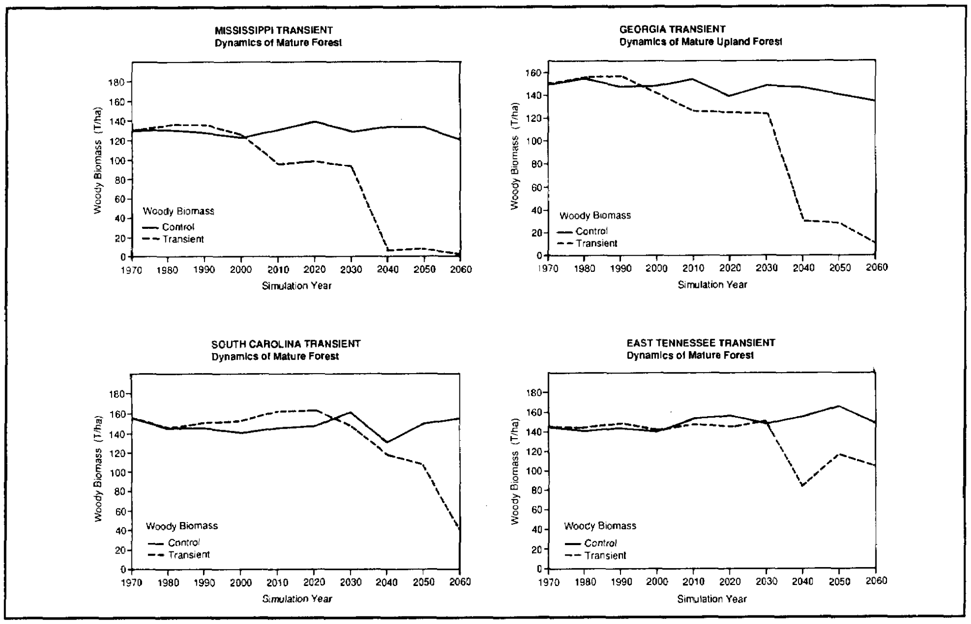


Figure 16-16. Response of southeastern forests to GISS transient scenarios of climate change (Urban and Shugart, Volume D).

Electric Utilities

Linder and Inglis (Volume H) examined the impact of global warming on the demand for electricity throughout the Southeast for the two GISS transient scenarios. (For additional details on the methods and limitations of this study, see Chapter 10: Electricity Demand.) Because their study was limited to electricity, it did not consider the reduced consumption of oil and gas for space heating that would result from warmer temperatures.

Table 16-10 shows the percentage changes in electric power requirements for various areas in the Southeast. Along the gulf coast, annual power requirements could increase 3 to 4% by 2010 and 10 to 14% by 2055; elsewhere, the increases could be somewhat less. Because peak demand for electricity generally occurs during extremely hot weather, peak demand would rise more than annual demand. (This result is also sensitive to changes in variability.)

Linder and Inglis compared increases in electric capacity required by climate change with those necessitated by economic growth. They estimated that through 2010, climate change could increase the expected capital costs of $137 billion by 6 to 9%; through 2055, it could increase expected requirements of $350 to $500 billion by as much as 20%.

COASTAL LOUISIANA

The sediment washing down the Mississippi River has formed the nation's largest delta at the river's mouth, almost all of which is in Louisiana. Composed mostly of marsh, cypress swamps, and small "distributary” channels that carry water, sediment, and nutrients from the river to these marshes and swamps, Louisiana's wetlands support half of the nation's shellfish, one-fourth of its fishing industry, and a large trapping industry. They also provide flood protection for metropolitan New Orleans and critical habitats for bald eagles and other migratory birds.

Water management and other human activities of the last 50 years are now causing this delta to disintegrate at a rate of about 100 square kilometers per year. Sediment that used to replenish the delta now largely washes into the deep waters of the gulf because flood-control and navigation guide levees confine the flow of the river. Thus, the delta is gradually being submerged, and cypress swamps are converting to open-water lakes as saltwater penetrates inland. If current trends continue, almost all the wetlands will be lost in the next century.

Table 16-10. Percentage Increases in Peak and Annual Demand for Electricity by 2010 and 2055 as a Result of Climate Change

Area	GISS A (2010)		GISS B (2010)		GISS A (2055)	
	Annual	Peak	Annual	Peak	Annual	Peak
North Carolina, South Carolina, Georgia	1.6	7.3	1.3	2.4	5.9	24.4
Florida	2.7	4.9	2.7	3.6	9.3	20.0
Eastern Tennessee	1.6	3.7	1.3	1.2	5.9	12.2
Alabama, Western Tennessee	1.9	3.8	2.2	5.7	6.8	13.5
Mississippi	3.8	7.6	4.4	11.4	13.6	6.9
Louisiana	2.9	7.6	2.7	6.6	10.2	23.4
East Texas	3.1	7.9	2.8	6.6	11.3	25.3

Source: Linder and Inglis (Volume H).

A rise in sea level would further accelerate the rate of land loss in coastal Louisiana. As shown in Figure 16- 17, even a 50-centimeter rise in sea level (in combination with land subsidence) would inundate almost all of the delta and would leave New Orleans, most of which is below sea level and only protected with earthen levees, vulnerable to a hurricane.

Strictly speaking, the entire loss of coastal Louisiana's estuaries should not be attributed to global warming because the ecosystem is already being lost. However, major efforts are being initiated by the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, the Louisiana Geological Survey, several local governments, and other federal and state agencies to curtail the loss, generally by erecting structures to provide freshwater and sediment to the wetlands. Technical staff responsible for developing these solutions generally fear, however, that a 1-meter rise in sea level could overwhelm current efforts, and that if such a rise is ultimately going to take place, they already should be planning and implementing a much broader effort (Louisiana Wetland Protection Panel, 1987).

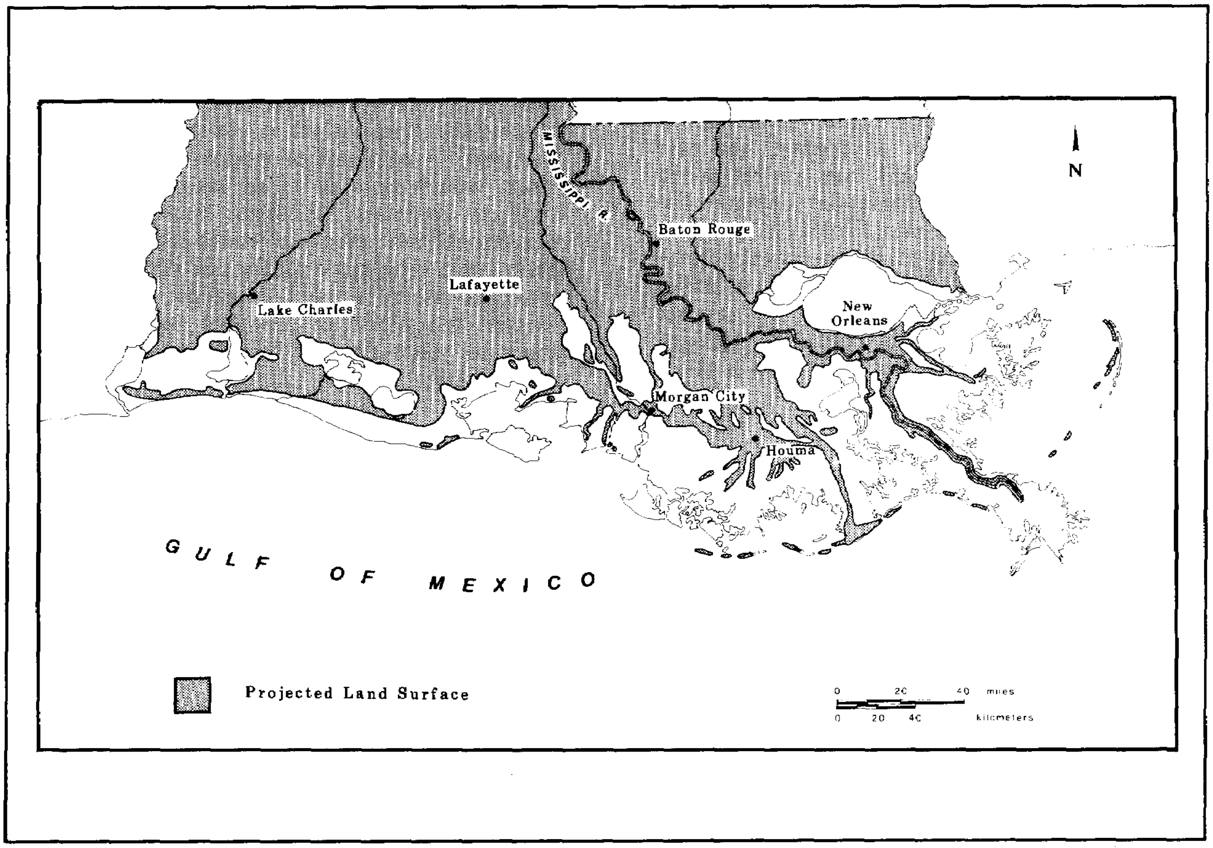


Figure 16-17. Projected future coastline of Louisiana for the year 2033, given a rise in sea level of 55 cm as predicted in the high scenario (Louisiana Wetland Protection Panel, 1987).

POLICY IMPLICATIONS

Agriculture and Forests

Climate change could have a major impact on land use in the Southeast. The estimated abandonment of 10 to 50% of the farmland in the Southeast and large declines in forests raise the an important question: How will this land be used?

In the past, forests have been cleared for agriculture, and when abandoned, they have been converted to forest again. But the forest models suggest that the impact of climate change on the generation of new forests from bare ground would be even more adverse than the impact on existing forests. If the forest simulations are correct, the abandoned fields would become grasslands or would become overgrown with weeds, and the Southeast could gradually come to resemble the scenery found today in the Great Plains.

However, no one has systematically investigated the extent to which human infrastructure might stabilize these changes. Changes in crops might enable more farms to stay in business than Adams et al. project, and new varieties of trees may find the region more hospitable. Because the commercial forests in the Southeast generally have short rotation cycles, it may be easier to respond to climate change there than in other regions. To a large degree, the ability of human intervention to maintain the present landscape would depend on international prices of agricultural and forest products, estimation of which is outside the scope of this report.

Water Resources

The water resource problems faced by the Southeast are not likely to be as severe as the problems faced by other regions of the country. Rainfall and runoff were estimated to increase in the GISS scenario. Although most other assessments suggest that runoff would decline, the magnitude of the decline does not appear to threaten the availability of water for municipal, industrial, or residential use. However, the nonconsumptive uses for hydropower, navigation, environmental quality, and recreation could be threatened. Although sufficient time exists to develop rational strategies to implement the necessary tradeoffs, current federal statutes constrain the ability of water managers to do so.

Impacts of Wetter Climate

Although most water resource problems have been associated with too little water, it does not necessarily follow that a wetter climate would be generally beneficial. The designs of water management infrastructure and the location of development along lakes and rivers have been based on current climate. Hence, shifts in either direction would create problems.

The chief problem from a wetter climate would be more flooding, particularly in southern Florida and coastal Louisiana, where water often lingers for days and even weeks after severe rainstorms and river surges. Inland communities, such as Chattanooga, also might face flooding if wetter periods exceed the ability of dams to prevent flooding.

Impacts of Drier Climate

A drier climate, on the other hand, would exacerbate current conflicts over water use during dry periods. Hydropower would decline, increasing the need to use fossil or nuclear power, both of which would require more water for cooling. Conflicts between municipal water users and recreational interests also would intensify. Lake levels could drop more during the summer, even if municipal use of water did not grow. However, warmer temperatures probably would increase municipal water demand for cooling buildings and watering lawns.

These conflicts could be further exacerbated if farmers increase the use of irrigation. Groundwater is available in reasonably shallow aquifers that drain into rivers. Any consumptive use of water from these aquifers would reduce, and in some cases reverse, the base flow of water from aquifers into these rivers. Water also could be drawn directly from rivers for irrigation in some areas.

A decline in riverflows could be important for both navigation and environmental quality. For the Tennessee, as well as the Chattahoochee and other small rivers, adequate reservoir capacity exists to maintain flows for navigation, if this use continues to take precedence over water supply and recreation. However, the 1988 drought has graphically demonstrated that there are not enough dams to guarantee navigation in the Mississippi. If this situation became more commonplace, the economic impact on New Orleans could be severe. On the other hand, traffic on the Tennessee and Ohio Rivers might use the Tennessee-Tombigbee Canal as an alternative, which would benefit the Port of Mobile.

Lower flows also would reduce the dilution of municipal and industrial effluents discharged into rivers and would decrease the level of dissolved oxygen. This would directly harm fish populations and would cause indirect harm by reducing the abilities of streams to assimilate wastes. Reduced flows also would threaten bottomland hardwood and estuarine ecosystems. To prevent these problems, factories and powerplants might have to erect cooling towers or curtail their operations more frequently.

Is Current Legislation Adequate?

The same issues that face the TVA and Lake Lanier would likely face decisionmakers in other areas. Federal laws discourage water managers in the Southeast from rigorously evaluating the tradeoffs between the various uses of water. Most dams are more than sufficient to meet the statutory requirements for navigation and flood safety and to continue generating substantial hydropower on demand. Consequently, there has been little need to analyze the tradeoffs between these factors. For example, a literal application of the law would not allow the U.S. Army Corps of Engineers to cut hydropower production or navigation releases to ensure a supply of water for Atlanta. Therefore, agencies have not analyzed the allocation of water that best serves the public for various levels of water availability (although the TVA is beginning to do so).

At a practical level, federal water managers have shown flexibility, as in the case of cutting navigation along the Chattahoochee instead of further cutting Atlanta's water supply. If climate changes and more than a modest level of flexibility is necessary, water resource laws could be changed; the physical infrastructure is largely in place to address water problems of the Southeast. But until the laws are changed, the federal agencies in the Southeast often would be forced to allocate water inefficiently. Moreover, people making decisions concerning siting of recreational and industrial development, long-term water supply sources, powerplant construction, and other activities sensitive to the availability of water would risk basing their decisions on incorrect assumptions regarding the future allocation of water.

Estuaries

Coastal plants and animals across the Southeast may have difficulty surviving warmer temperatures. For example, along the northern coast of the Gulf of Mexico, several types of fish spend at least part of their lifetimes in estuaries that are already as hot as they can tolerate. If climate became warmer, however, migrating north would not be feasible. While these species could escape the summer heat by fleeing to the cooler waters of the gulf, such a flight would make them vulnerable to larger fish.

In addition to the direct effect of climate change on estuaries, human responses to climate change and sea level rise also could hurt coastal estuaries. Besides the impacts of flood control, increased reservoir construction would decrease the amount of sediment flowing down the river and nourishing the wetlands. If the climate becomes drier, irrigation could further reduce freshwater flow into estuaries.

To a large extent, the policy implications for wetland loss in the Southeast are similar to those facing the rest of the U.S. coastal zone. Previous studies have identified several measures to reduce the loss of coastal wetlands in response to sea level rise (e.g., Titus, 1988). These measures include the following:

- increase the ability of wetlands to keep pace with sea level;
- remove impediments to landward creation of new wetlands; and
- dike the wetlands and artificially maintain water levels.

All these measures are being employed or actively considered.

Congress has authorized a number of freshwater and sediment diversion structures to assist the ability of Louisiana's wetlands to keep up with relative sea level rise. These structures are engineered breaches in river levees that act as spillways into the wetlands when water levels in the river are high.

Although decisions on where to build diversion structures are being based on current climate and sea level, consideration of global warming would substantially change the assumptions on which current analyses are being based and the relative merits of alternative options. More frequent or higher surges in the Mississippi River would increase the amount of water delivered to the wetlands. And if climate change resulted in more soil erosion, more sediment might also reach the wetlands; lower flows could have the opposite effect. Sea level rise might shorten the useful lifetimes of these projects, but because the flood-protection benefits of protecting coastal wetlands would be greater with a higher sea level (Louisiana Wetland Protection Panel, 1987).

Artificially managing water levels also has been proposed for Louisiana, particularly by Terrebonne Parish, whose eastern wetlands are far removed from a potential source of sediment. Such an approach also might be possible for parts of Florida, where wetlands already are confined by a system of dikes and canals, and water levels already are managed. Although no one has yet devised a practical means by which shrimp and other fish could migrate between ocean and estuary, other species spend their entire lifetimes within the estuary, and freshwater species could remain in artificially maintained freshwater wetlands.

A final response would be to accept the loss of existing wetlands, but to take measures to prevent development from blocking the landward creation of new wetlands. This approach has been enacted by the State of Maine (1987) and would be consistent with the proposals to discourage bulkheads that have been widely discussed by coastal zone managers and enacted by the State of South Carolina. Titus and Greene estimate that 1,800 square miles of wetlands in the Southeast could be created if developed areas were not protected. Although this area represents a small fraction of the potential loss, it would increase the remaining areas of wetlands by 30 to 90%, and it would maintain and perhaps increase the proportion of shorelines on which at least some wetlands could be found.

Beach Erosion

The implications of sea level rise for recreational beaches in the Southeast are similar to the implications for the mid-Atlantic and the Northeast. If shore-protection measures are not taken, the majority of resorts will have no beach at high tide by 2025 under the midrange scenario of future sea level rise. The cost of undertaking the necessary measures through 2025 probably would be economically justified for most resorts (see Chapter 7: Sea Level Rise). However, the cost of protecting all recreational beaches through 2100 would be $100 to $150 billion, which would probably lead some of the more vulnerable areas to accept a landward migration much as areas on North Carolina's Outer Banks are facing today, particularly if warmer temperatures also lead to more hurricanes.

The potential responses to global warming should be viewed within the context of current responses to erosion flooding. Florida has a trust fund to nourish its beaches and has received federal assistance for pumping sand onto the shores of Miami Beach. Mississippi has nourished the beaches of Biloxi, Gulfport, and other resort communities that lie on the mainland along the protected waters behind the barriers. Louisiana is rebuilding its undeveloped barrier islands because they protect the mainland from storms. Most states are moving toward "soft engineering" solutions, such as beach nourishment, because of doubts about the effectiveness of hard structures in universal erosion and their interference with recreational uses of the beach.

Land-use measures also have been employed to adapt to erosion. Because of unusually high erosion rates on the Outer Banks, houses along the coast are regularly moved landward. North Carolina requires houses, hotels, and condominiums to be set back from the shore by the distance of a 100-year storm plus 30 years' worth of erosion on the assumption that after 30 years, the house could be moved back. Texas requires that any house left standing in front of the vegetation line after the shore erodes must be torn down.

If a global warming increases the frequency of hurricanes, a number of southeastern communities will be devastated. However, the overall impact of increased hurricane frequency would be small compared with the impact of sea level rise. While a doubling of hurricanes would convert 100-year floodplains to 50-year floodplains throughout much of the Southeast, a 1-meter rise would convert them to 15-year floodplains.

Because the open-coast areas most vulnerable to sea level rise are generally recreational beach resorts, the costs of erosion and flooding should be viewed within the larger context of why people go to the beach. People from the north visit southeastern beaches to escape winter, and residents of the region go to escape the summer heat. As temperatures become warmer, Georgia and the Carolinas may be able to compete with Florida for northerners. Hotter temperatures also may increase the desire of the region's residents to visit the beach.

Thus, it is possible that the cooler communities will reap benefits from a longer and stronger tourist season that are greater than the increased costs for erosion control. Areas that already have a year-round season are less likely to benefit, and in a few areas like Miami Beach, the off-season may be extended.

REFERENCES

Armentano, T.V., R.A. Park, and C.L. Cloonan. 1988. Impacts on coastal wetlands throughout the United States. In: Titus, J.G., ed. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Barth, M.C., and J.G. Titus. 1984. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Burnash Robert J.C., R.L. Ferral, and RA. Mcguire. 1973. A Generalized Streamflow Simulation System, Conceptual Modeling for Digital Computers. Sacramento, CA: National Weather Service and California Department of Water Resources.

Edison Electric Institute. 1985. Statistical Yearbook of the Electric Utility Industry. Washington, DC: Edison Electric Institute.

Geraghty, J., D. Miller, F. Van Der Leeden, and F. Troise. 1973. Water Atlas of the United States. Port Washington, NY: Water Information Center.

Gibbs, M. 1984. Economic analysis of sea level rise: methods and results. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Hansen, J., I. Fung, A. Lacis, D. Rind, G. Russell, S. Lebedeff, R. Ruedy, and P. Stone. 1988. Global climate change as forecast by the GISS 3-D model. Journal of Geophysical Research 93(D8):9341-9364.

Healy, R.G. 1985. Competition for Land in the American South. Washington, DC: The Conservation Foundation.

Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. College Station, TX: Texas A&M Press.

Kana, T.W., J. Michel, M.O. Hayes, and J.R. Jensen. 1984. The physical impact of sea level rise in the area of Charleston, South Carolina. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Leatherman, S.P. 1984. Coastal geomorphic responses to sea level rise: Galveston Bay, Texas. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. 1988. Potential Impacts of Climate Change on Electric Utilities. New York: New York State Energy Research and Development Authority.

Louisiana Wetland Protection Panel. 1987. Saving Louisiana's Coastal Wetlands: The Need for a Long-Term Plan of Action. Washington, DC: U.S. Environmental Protection Agency/Louisiana Geological Survey. EPA-230-02-87-026.

Meo, M. 1987. Proceedings of the Symposium on Climate Change in the Southern United States. Norman, OK: University of Oklahoma.

Mitch, W., and J. Gosselink. 1986. Wetlands. New York: Van Nostrand Reinhold Company.

NOAA. 1987. National Oceanic and Atmospheric Administration. Fisheries Statistics Division, National Marine Fisheries Service. 1987 Preliminary Statistics for United States Domestic Catch. Washington, DC: Unpublished data

Rind, D. 1988. The doubled CO_2 climate and the sensitivity of the modelled hydroloc cycle. Journal of

Geophysical Research.

Shugart, H.H., and D.C. West. 1977. Development of an Appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight. Journal of Environmental Management 5:161-179.

State of Maine. 1987. Dune Rule 355. Augusta, ME: Maine Department of Environmental Protection.

Titus, J.G. 1987. The greenhouse effect, rising sea level, and society's response. In: Devoy, R.J.N., ed. Sea Surface Studies. New York: Croom Helm.

Titus, J.G. 1988. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, DC: US. Environmental Protection Agency.

Titus, J.G. 1988. Sea level rise and wetland loss: an overview. In: Titus, J.G., ed. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, DC: U.S. Environmental Protection Agency.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Welts, and J.O. Waddell. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. Journal of Water Resource Planning and Management ASCE 113(2):216-227.

Titus, J.G. 1984. Planning for sea level rise before and after a coastal disaster. In: Barth, M.C., and J.G. Titus, eds. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

U.S. Department of Agriculture. 1987. Agricultural Statistics: 1987. Washington, DC: U.S. Department of Agriculture.

U.S. Department of Commerce. 1988. U.S. Department of Commerce, Bureau of the Census. Statistical Abstract of the United States: 1988. Washington, DC: Government Printing Office.

U.S. Department of Commerce. 1986. U.S. Department of Commerce, Bureau of Economic Analysis.

U.S. Department of Commerce. 1982. U.S. Department of Commerce, Bureau of the Census. Census of Agriculture. Vol. 1. Geographic Area Series. Washington, DC: Government Printing Office.

U.S. Department of Energy. 1988. U.S. Department of Energy, Energy Information Administration. Electric Power Monthly; May.

U.S. House of Representatives. Rep. Jenkins, Rep. Barnard, Rep. Darden. HR-4254. Georgia Reservoir Management Improvement Act of 1988. 100th Congress, 20th Session.

Wilkerson, G.G., J.W. Jones, K.J. Boote, and J.W. Mishoe. 1985. SOYGRO V5.0: Soybean Crop Growth and Yield Model. Technical Documentation. Gainesville, FL: University of Florida.

CHAPTER 17
GREAT PLAINS

FINDINGS

Agriculture in the Great Plains (this study focused on Nebraska, Kansas, Oklahoma, and Texas) is sensitive to climate fluctuations and would be at risk from global warming. Although uncertainties remain regarding the rate and magnitude of global climate change and the models used to estimate impacts, results indicate that climate change would cause reductions in regional agricultural production. Demand for irrigation is likely to increase, and quality of water may diminish. Regional electricity use may increase.

Agriculture

- The effects of a warmer climate alone would generally reduce wheat and corn yields. Yield changes range from + 15 to -90%. The direct effects of CO_2 on crop photosynthesis and water use may mitigate these effects, but the extent to which the beneficial effects of CO_2 on crop yields would be seen with climate change is uncertain.

- Crop yields in Texas and Oklahoma may decline relative to northern areas of the United States. This change in productivity could lead to a 4 to 22% reduction of cultivated acreage in these states.

- Because of increased reliability of yields from irrigated lands relative to dryland yields, and because of potentially higher crop prices, demand for irrigation water on remaining farms would probably increase as global warming proceeds. The number of acres irrigated may increase by 5 to 30%.

Ogallala Aquifer

- Warming and/or drying in the Great Plains may place greater demand on regional groundwater resources. Many of the problems associated with intense groundwater use -- water depletion,soil damage, altered farm and rural economics, and potential reversion to dryland farming – could be exacerbated by global warming.

Water Quality

- It is not clear how climate change would affect water quality in the Great Plains. Groundwater quality may be less at risk than surface water quality because of increased evaporation and less leaching. These results are very sensitive to changes in the amounts and frequency of rainfall, and groundwater impacts will be affected by total acres under production, by application rates, by soil type under cultivation, and by changes in irrigated versus dryland acres.

Electricity Demand

- Climate warming could cause the annual demand for electricity in Kansas, Nebraska, Oklahoma, and West Texas to rise by an additional 5 to 9 billion kilowatthours (kWh) (2 to 4%) by 2010, and by an additional 37 to 73 billion kWh (10 to 14%) by 2055. Summertime use for air-conditioning and irrigation pumping could increase and outpace reductions in winter demand for space heating.

- Approximately 3 to 6 gigawatts (GW) of generating capacity would be needed by 2010 to meet the additional increased demand, and 22 to 45 GW would be needed by 2055 -- a 27 to 39% increase over baseline additions that may be needed without climate change. The cumulative cost of these additions by 2055 would be $24 to $60 billion.

Policy Implications

- Agencies with responsibility for agricultural land use, such as the U.S. Department of Agriculture (USDA) Agricultural Stabilization and Conservation Service and the Soil Conservation Service, should begin to analyze how their missions may be affected by climate change and to consider development of flexible strategies to deal with potential impacts. Water resource managers, such as those on river basin commissions and in state natural resource agencies, may wish to factor the potential effects of climate change into planning of land use, long-term water supply, irrigation, drainage, and water-transfer systems.

CLIMATE-SENSITIVE RESOURCES IN THE GREAT PLAINS

The Great Plains consists of a predominantly treeless region of relatively flat topography between the Rocky Mountains and the Mississippi lowlands of central North America. Although very productive, the region (Figure 17-1) is sensitive to climate fluctuations, a fact that has been made apparent in several major droughts over the last few decades.

Despite this climate sensitivity, dryland agriculture provides the chief economic base for this thinly populated region with few cities. The region was first settled by farmers in the late 1800s under the Homestead Act, which created the family-farm system in place today in the Plains (Bowden et al., 1981).

The Great Plains, including portions of Nebraska, Kansas, Oklahoma, and Texas, constitutes a vital part of the United States' agricultural base and is the focus of this report. Nearly 100,000 farms encompassing over 111 million acres produce an important array of dryland and irrigated crops. Major dryland crops include winter wheat and grain sorghum, and key irrigated grains include corn and rice. In all, the four states have a combined production of over 80, 30, and 25% of the nation's grain sorghum, wheat, and cotton, respectively (Table 17-1).

Exploitation of water from the Ogallala Aquifer has supported significant irrigated agricultural production in the Great Plains during the last two decades. In many areas, irrigated farming of corn, rice, and cotton has replaced dryland wheat production, especially in western Kansas and the Texas Panhandle (Figure 17-1). However, the region's groundwater resources have been overexploited in some areas, leading to some reversion to dryland cropping.

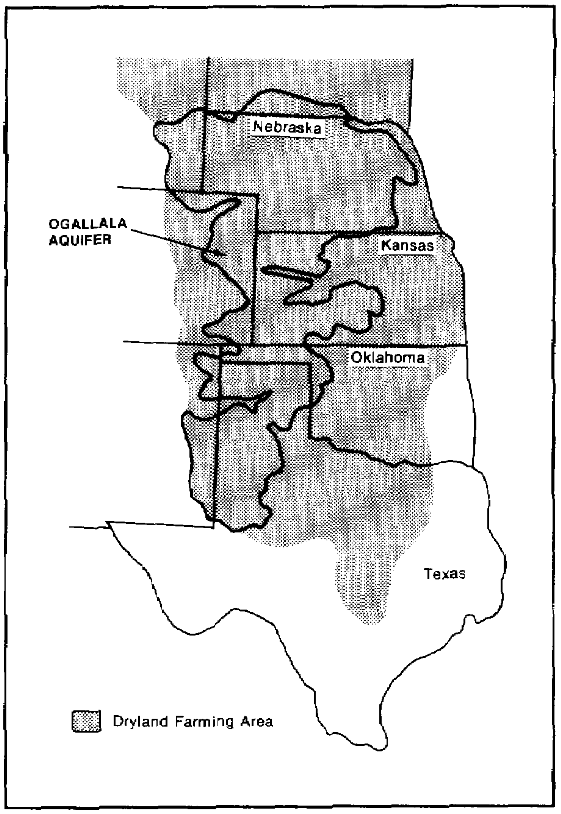


Figure 17-1. Boundaries of the Ogallala Aquifer and dryland wheat production in the Great Plains (Science of Food and Agriculture, 1987, 1988).

Livestock constitute another important agricultural commodity in the region. Almost 50% of all cattle fattened in the country are raised in the four states, accounting for 40% of the total U.S. value of marketed livestock.

In addition to contributing substantially to national food supplies, the four states are also major exporters of agricultural products. Foreign exports of grain and animal products are especially notable (Table 17-2). In total, these four states provide approximately one-fifth of the dollar value of all U.S. agricultural

Table 17-1. U.S. Agricultural Ranking for Great Plains States and Percent of U.S. Total (for the four states combined) for Selected Products, 1982

Product	Kansas	Nebraska	Oklahoma	Texas	U.S. total (all four states) (%)
Sorghum harvested	2	3	5	1	80.5
Cattle fattened on grain and concentrates sold	2	3	9	1	46.7
Value of cattle and calves sold	2	3	7	1	40.7
Wheat harvested	1	9	3	6	31.8
Cotton harvested	--	--	9	2	25.8
Hay harvested	9	2	16	7	15.9
Market value of all agricultural products	6	5	20	3	18.5

Source: USDA (1983).

Table 17-2. Agricultural Exports From Selected Great Plains States, Fiscal Year 1984 (millions of dollars)

Exports	U.S.	Kansas	Nebraska	Oklahoma	Texas	U.S. total (%)
Feed grains and byproducts	7,585	372	903	-	385	22
Wheat and byproducts	4,526	797	150	353	276	35
Live animal and meats	1,161	130	134	18	161	38
All agricultural products	31,187	1,719	1,762	1,471	2,031	19

Source: USDA (1985).

exports. Yet, dependence on foreign markets puts Great Plains farmers at high risk. While large historical fluctuations in grain and livestock production levels are partly related to climatic variability, changing international demand, and its effects on price, play an important role in the region's continuing economic and social instability.

The Great Plains is also a major source of coal and oil, though such extractive industries vary more with international energy markets than with climate. Otherwise, the area exhibits little economic diversity, a pattern that has led to a net outmigration, especially of younger segments of the population. Regional population is growing slowly mostly in the fringe cities (e.g., Omaha), while rural population and the total number of farms are slowly decreasing. The region's economy remains inexorably linked to the fortunes of agriculture and, thus, to the climate.

Dryland Agriculture

The dryland farming area of the Great Plains is one of the most marginally productive agricultural regions in the United States. Some observers have stated that the southern Plains are simply too sensitive to climate swings and that intensive dryland farming should be abandoned (Worster, 1979; Popper and Popper, 1987). Yet in many years, the Plains produce bumper crops of small grains that add significantly to the nation's export trade balance.

Dryland farmers in the Great Plains are particularly vulnerable to climate variability. The Great Plains States of Nebraska, Kansas, Oklahoma, and Texas were the hardest hit during the Dust Bowl of the 1930s (Worster, 1979; Hurt, 1981). Yields of wheat and corn dropped as much as 50% below normal, causing the failure of about 200,000 farms and migration of more than 300,000 people from the region.

The Dust Bowl, other droughts, and the desire for continued expansion and intensification of dryland farming have led to numerous technological and social adjustments to climate and market fluctuations. Especially critical, from a dryland farming perspective, has been the improvement of conservation tillage practices like summer fallowing (Warrick and Bowden, 1981; Riebsame, 1983). These practices are designed to conserve moisture, reduce energy input, and minimize erosion, and thus, to increase yields and profits. Nevertheless, dryland crop yields still fluctuate widely with temperature and precipitation variations between years. The coefficient of variation of wheat yields is close to 50% over much of the region, and approximately 30-40% of the planted acreage is abandoned every year because of poor crops, especially on the western fringes of agriculture where the dominant crop is dryland wheat grown on summer fallow (Michaels, 1985).

In addition to the developments in cropping systems, government policies and programs have also been devised to absorb or mitigate the impacts of climate stresses in the Great Plains and elsewhere. These include federal programs for crop insurance, disaster grants and low-interest loans to farmers, and government-sponsored drought research (Warrick, 1975). Such programs can be costly. For example, the projected cost of the 1988 Drought Relief is about $3.9 billion nationally (Schneider, 1988).

Despite the adoption of conservation tillage techniques, drought-resistant cultivars, and risk management programs, some analysts argue that the region remains particularly vulnerable to climate-induced reductions in crop yields and will be one of the first U.S. agricultural regions to exhibit impacts of climate change (e.g., Lockeretz, 1978; Warrick, 1984). Rapid acreage increases in the 1970s, destruction of windbreaks for larger fields to accommodate bigger machinery, and speculative farm expansion all raise the possibility of renewed land degradation and economic losses similar to those of the Dust Bowl period, if climate change creates an increased frequency of heat waves and droughts in the region. Most climate models indicate that the region would become drier as global warming proceeds, suggesting potentially severe impacts on dryland farming.

Irrigated Agriculture

One response to the semiarid and highly variable climate of the Great Plains has been exploitation of surface and groundwater resources for irrigation to replace dryland farming. In 1982, 19 million acres, or 12% of all Great Plains cropland, mostly in the southern Plains, were irrigated. Groundwater provides most of the water for irrigation: 61 to 86% of the water used in Nebraska, Oklahoma, and Kansas as compared with only 20% nationally. In this respect, irrigation farmers in the Great Plains are less sensitive to climate change relative to dryland farmers. However, the demand for irrigation water throughout the region is very sensitive to climate.

The improvement and application of well drilling and pumping technology after World War 11 permitted the use of water from the immense Ogallala Aquifer (Figure 17-1). Today, the aquifer supplies irrigation for approximately 14 million acres in the Great Plains States of Colorado, Nebraska, Kansas, Oklahoma, New Mexico, and Texas (High Plains Associates, 1982). Use of the aquifer allows the irrigation of terrain too far from surface supplies. The aquifer also provides water for municipal and industrial purposes.

Farmers in Nebraska recently began to use the aquifer to irrigate corn, which is grown mostly for livestock feed. Corn, wheat, and some sugarbeets are irrigated farther south, while in Texas the Ogallala is tapped chiefly for cotton. The aquifer varies in depth from the land surface, in rate of natural discharge, and in saturated thickness across the region. In Nebraska, the aquifer has a higher recharge rate (i.e., the rate at which the aquifer is replenished) than in the other Great Plains States, and significant drawdown problems have not yet occurred. In Texas and other states, high withdrawal and low recharge rates of the aquifer have already resulted in "mining" of the resource (i.e., the rate of water withdrawal is greater than rate of recharge) and in the abandonment of thousands of irrigated acres (see Glantz et al., Volume 7).

Water Quality

Nonpoint pollution (runoff and leaching) is the main contributor to water quality problems in the Great Plains. Many of the groundwater supplies in the region contain elevated levels of fertilizer and pesticide-derived pollutants.

Electricity Demand

Electricity use in the region is sensitive to climate fluctuations in terms of space heating, cooling, and agricultural operations such as irrigation and livestock management (heating, cooling, etc.). Other types of energy are also sensitive to climate, but this study addresses only electricity.

PREVIOUS CLIMATE IMPACT STUDIES

Many studies of climate impacts on agriculture in the Great Plains have been performed using a variety of approaches and models. Dozens of climate impact studies have focused specifically on the 1930s drought (e.g., Lockeretz, 1978; Bowden et al., 1981) and, more generally, on Great Plains droughts (Warrick, 1975). Many recent studies have used crop-climate models to estimate impacts of climate on yields. Warrick (1984) analyzed the vulnerability of the region to a possible recurrence of the 1930s drought by running a dryland crop yield model tuned to 1975 technology with 1934 and 1936 temperature and precipitation conditions. He found that recurrence of 1930s conditions in the region would result in wheat yield reductions of over 50%. Terjung et al. (1984) used a crop water demand and yield model to investigate irrigated corn production sensitivity to differing temperature, precipitation, and solar radiation fluctuations. They found that in the central Great Plains, evapotranspiration and total water applied for irrigation were very sensitive to climate variations. Liverman et al. (1986) continued this modeling and found that the lowest irrigated yields occurred under cloudy, hot, and very dry climate scenarios. Under dryland cropping, minimum yields occurred under sunny-hot and sunny-warm scenarios with very dry conditions.

Using an agroclimatic approach, Rosenzweig (1985) found that lack of cold winter temperatures in the southern Great Plains may necessitate a change from winter to spring wheat cultivars with climate change projected for a doubling of CO_2. Changes in temperature, precipitation, and solar radiation were considered. Decreased water availability may also increase demand for irrigation. In a later study, Rosenzweig (1987) showed that although the combined impact of doubled CO 2 climate change (temperature, precipitation, and solar radiation changes) and the direct effects of elevated CO_2 (increased photosynthesis and improved water use) compensated for the negative effects of climate change in years with adequate rainfall, this compensation did not reduce crop failures in dry years.

Robertson et al. (1987) estimated the combined impact of temperature and precipitation changes due to doubled CO_2 climate change and the direct effects of increased CO_2 on rainfed corn and wheat yields and erosion using the Erosion Productivity Impact Calculator (EPIC). Results showed that modeled wheat yields in Texas decreased and modeled corn yields increased slightly. Such changes in productivity could result in long-term changes in cropping patterns.

Glantz and Ausubel (1984) suggested that the Great Plains' mining of the Ogallala Aquifer and its susceptibility to future incidence of drought projected by global climate models be combined in analyses of the region, since both are critical to the habitability of the area.

GREAT PLAINS STUDIES IN THIS REPORT

The studies for this report examine the implications of climate change for several important activities in the region: agricultural production and economics, demand for irrigation water, and water quality. Climate change impact research on livestock, electricity use, and resource management policy relevant to the Great Plains is also described. The individual studies performed for this report are listed in Table 17-3.

The Great Plains studies explore the sensitivities of regional activities to climate change scenarios. The results are not meant to be predictions of what will happen; rather the studies aim to define the ranges and magnitudes of potential responses of critical regional systems to the predicted climate changes.

GREAT PLAINS REGIONAL CLIMATE CHANGE SCENARIOS

The estimated changes in seasonal and annual temperatures and precipitation for the scenarios are shown in Figure 17-2. For a description of the global climate models, climate scenarios, and a discussion of the likelihood of these changes, see Chapter 2: Climate Change, and Chapter 4: Methodology. All three scenarios show large increases in temperature for the Great Plains States under a doubled CO_2 climate. The GISS scenario has an annual warming of 4.5°C, the GFDL scenario has an annual warming of 5.0°C, and OSU has an annual warming of 3.3°C. In general, winter temperatures increase more than summer temperatures in the GISS model, and summer temperature changes are greater than winter temperature changes in the GFDL and OSU scenarios. The differences between the models range from 0.2 to 1.5°C. The impact studies used only the GISS and GFDL climate change scenarios because of time limitations.

Average annual precipitation decreases by 0.26 millimeters per day (3.7 inches per year) in the GISS scenario, while GFDL and OSU have slight increases. However, these annual values mask a pronounced reduction in rainfall in Nebraska and Kansas in the GFDL scenario (see Figure 17-3). The large temperature increase and pronounced summer drying combine to make the GFDL scenario severe in these states, and the most severe case among the climate change scenarios.

The magnitudes of climate changes in the spring and summer from the GFDL scenario and the climate of the 1930s drought in Nebraska and Kansas are compared in Figure 17-3. While the scenario decreases in growing season precipitation are about the same as those during the most severe drought years (1934 and 1936) in the area, the climate change scenario temperatures are about 3°C higher than the Dust Bowl temperatures.

Table 17-3. Great Plains Studies for EPA Report to Congress on the Effects of Global Climate Change

Analyses Performed for This Case Study

- Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study - Rosenzweig, Columbia University, NASA/Goddard Institute for Space Studies (Volume C)
- Effects of Projected CO_2-Induced Climatic Changes on Irrigation Water Requirements in the Great Plains States - Allen and Gichuki, Utah State University (Volume C)

National Studies That Included Great Plains Results

- Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment - Adams, Oregon State University and Glyer and McCarl, Texas A&M University (Volume C)
- Impacts of Climate Change on the Movement of Agricultural Chemicals Across the U.S. Great Plains and Central Prairie -Johnson, Cooter, and Sladewski, Oklahoma Climatological Survey, University of Oklahoma (Volume C)
- Changing Animal Disease Patterns Induced by the Greenhouse Effect - Stem, Mertz, Stryker, and Huppi, Tufts University (Volume C)
- Effect of Climatic Warming on Populations of the Horn Fly, with Associated Impact on Weight Gain and Milk Production in Cattle - Schmidtmann and Miller, U.S. Department of Agriculture, Agricultural Research Service (Volume C)
- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates - Linden and Inglis, ICF Incorporated (Volume H)
- Climate Change and Natural Resources Management in the United States - Riebsame, University of Colorado (Volume J)

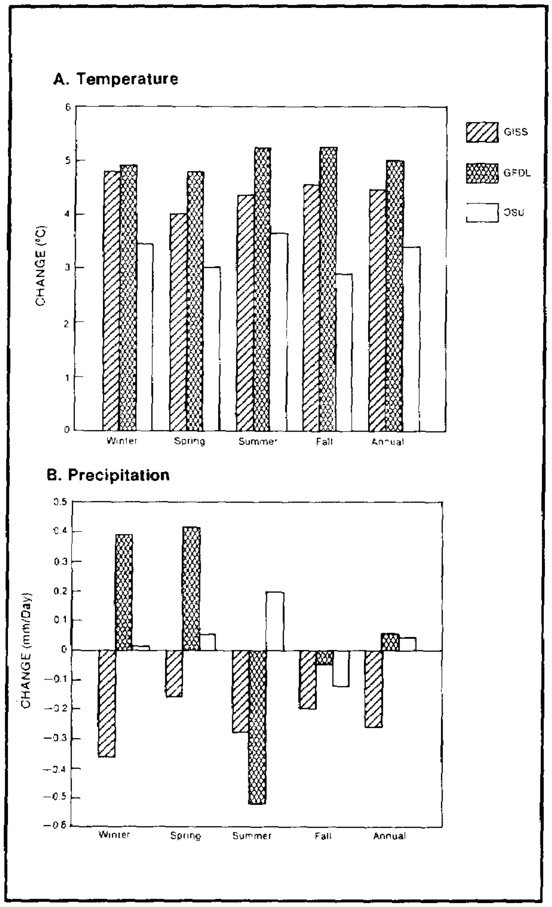


Figure 17-2. Average change in (A) temperature, and (B) precipitation over Great Plains gridpoints in GISS, GFDL, and OSU global climate models (2X CO_2 run less 1X CO_2 run).

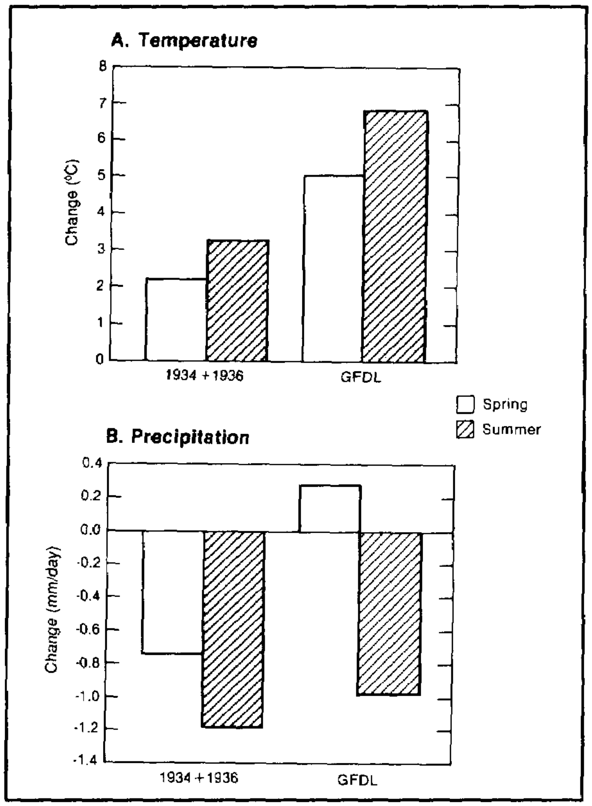


Figure 17-3. Comparison of observed drought (1943 and 1936) and GFDL climate change in Nebraska and Kansas for (A) temperature, and (B) precipitation (Rosenzweig, Volume C).

RESULTS OF THE GREAT PLAINS STUDIES

Crop Production

To better understand the potential physical impact of climate change on crops, Rosenzweig modeled changes in corn and wheat yields in the Great Plains using crop growth models.

Study Design

Two crop growth models, CERES-Wheat (Ritchie and Otter, 1985) and CERES-Maize (Jones and Kiniry, 1986) were used to test the sensitivity of crop yields to the GISS and GFDL climate change scenarios. These models are designed for large-area yield prediction and for farm decisionmaking and have been validated for a wide range of conditions (Otter-Nacke et al., 1986). The CERES models simulate crop responses to the major factors that affect crop yields: climate, soils, and management. The models employ simplified functions to predict crop growth stages; development of vegetative and reproductive structures; growth of leaves and stems; dieback of leaves; biomass production and use; root system dynamics; and the effects of soil-water deficit on photosynthesis and biomass use in the plant.

At each of 14 locations, the crop models were run with three soils present in the region representing low, medium, and high productive capacity. Model results were generated for changes in yield, water used for irrigation (if crop is irrigated), crop evapotranspiration, and planting and maturity dates for both dryland and irrigated cases. The direct effects of CO_2 (i.e., increased photosynthesis and decreased transpiration per unitleaf area) were simulated with the climate change scenarios in another set of runs. A method for approximating the direct effects in the CERES models was developed by computing ratios of daily photosynthesis and evapotranspiration rates for a canopy exposed to elevated (660 ppm) CO_2 to those rates for the same canopy exposed to current (330 ppm) CO_2 conditions (see Peart et al., Volume C). Daily photosynthesis rates of wheat and corn canopies were increased 25 and 10%, respectively, based on published results of controlled environmental experiments with crops growing in air with increased CO_2 levels.

Limitations

This work does not consider changes in frequencies of extreme events, even though extremes of climatic variables, particularly runs of extremes, are critical to crop productivity (see Chapter 3: Variability). Development of the CERES models was based on current climate; the relationships in the models may or may not hold under differing climate conditions, particularly the high temperatures predicted for greenhouse warming.

The direct effects of CO_2 are only approximated in the crop modeling study, because the models do not include a detailed simulation of photosynthesis. Also, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (e.g., weeds, insects, and diseases) field conditions; thus, this study probably overestimated the beneficial effects of increased CO_2.

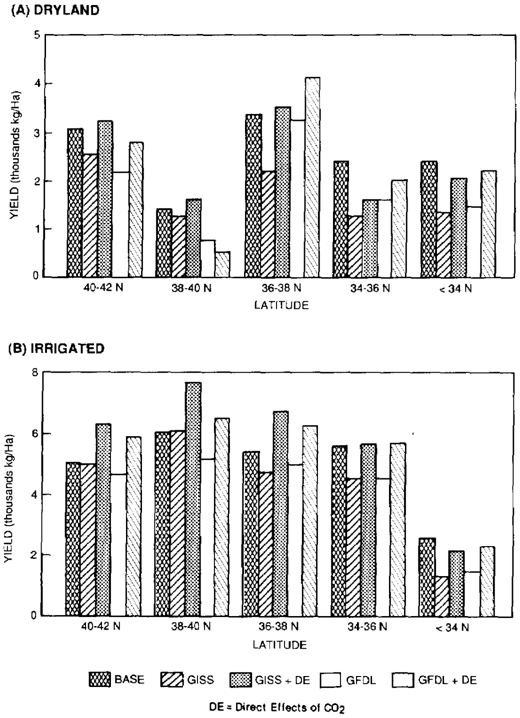


Figure 17-4. CERES-Wheat yields in the Great Plains with GISS and GFDL climate change scenarios with and without the direct effects of CO_2: (A) dryland, (B) irrigated (Rosenzweig, Volume C).

Results

Climate change scenarios cause simulated wheat (Figure 17-4) and corn (Figure 17-5) yields to decrease in the southern and central Great Plains. Results shown are means of modeled yields at study sites grouped by latitude for 30 years of baseline and climate change scenarios. With climate change alone, decreases in modeled yields appear to be caused primarily by increases in temperature, which would shorten the duration of crop life cycle (the period during which a crop grows to maturity). This results in reduced yields. When the direct effects of CO_2 on crop photosynthesis and transpiration are included in the climate change simulations, modeled crop yields overcome the negative effects of climate change in some cases, but not in others. In general, the more severe the climate change scenario, the less compensation provided by direct effects of CO_2.

Corn and wheat yields were estimated to respond differently to dryland and irrigated climate change conditions and to the direct effects of CO_2. Dryland corn yield decreases were very high in the hotter and drier GFDL scenario, particularly at higher latitudes. These decreases were caused by the combined effects of high temperatures shortening the grain-filling period and increased moisture stress. The GFDL scenario has pronounced reductions in summer precipitation (decreases of about 30 mm per month) in the two northern gridboxes of the study area, which occur during critical growth stages of corn. Irrigated corn was more negatively affected than irrigated wheat in the combined climate and direct effects runs because of the lower photosynthetic response of corn to CO_2.

In general, the amount of water needed for irrigation in the crop models is estimated to increase in the areas where precipitation decreases and irrigation reduces interannual variability in yields. These results suggest an increased demand for irrigation in the region.

Adjusting the planting date of wheat to later in the fall, one potential farmer adjustment to a warmer climate, was not estimated to significantly ameliorate the effects of the GISS climate change scenario on CERES-Wheat yields. Changing to varieties with lower vernalization requirements (need for a period of cold weather for reproduction) and lower photoperiod sensitivity (sensitivity to daylength), in addition to delaying planting dates, overcomes yield decreases at some sites but not at others.

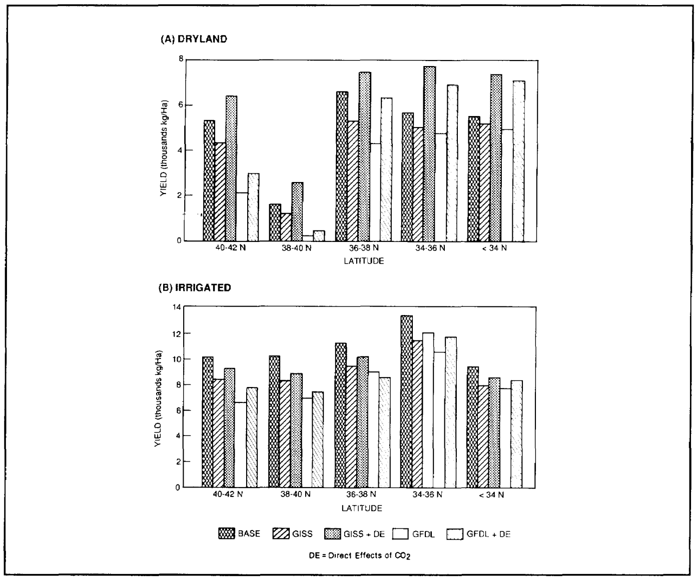


Figure 17-5. CERES-Maize yields in the Great Plains with GISS and GFDL climate change scenarios with and without the direct effects of CO_2: (A) dryland, (B) irrigated (Rosenzweig, Volume C).

Table 17-4. Estimated Changes in Agricultural Land Usage in Oklahoma and Texas (millions of acres)

Usage	Base acreage	GISS			GFDL		
		Acreage	Change	% Change	Acreage	Change	% Change
Agricultural land							
Without direct effects	54.7	42.6	-12.1	-22.1	52.0	-2.7	-4.9
With direct effects	54.7	48.8	-10.9	-19.9	52.7	-2.0	-3.8
Irrigated acreage							
Without direct effects	5.3	6.9	1.6	29.6	5.6	0.3	4.9
With direct effects	5.3	5.8	0.5	9.4	6.1	0.8	15.3

Source: Adams et al. (Volume C).

Implications

There is potential for climate change to cause decreased crop yields in the southern Great Plains. Farmers would need varieties of corn and wheat that are better acclimated to hotter and possibly drier conditions to substitute for present varieties, and adjustment strategies tailored for each crop and location.

Pressure for increased irrigation may grow in the region, particularly with more severe climate changes. This would occur for two reasons: first, crops currently irrigated would require more water where precipitation decreases; and second, more acreage would be irrigated as high temperatures increase the risk of crop failures. Increased irrigation would be needed to ensure acceptable and stable yield levels. However, availability of and competition for water supplies also may change with climate change, and defining the extent to which irrigation can provide an economic buffer against climate change requires further study.

Agricultural Economics

Many economic consequences are likely to result from the physical changes in crop yields and water availability caused by climate change. Decreased yields will further stress farmers already affected by marginal productivity and economic fluctuations. Additional irrigation needs could place greater demand on the Ogallala Aquifer and other water resources in the region. To examine the agricultural implications of climate change more closely, Adams et al. introduced yield changes from the Great Plains and other regional crop modeling studies, and changes in crop water use and water availability from the GISS and GFDL scenarios into an economic model to translate the physical effects of climate change into economic consequences. (For study design and limitations, see Chapter 6: Agriculture.) Analyses were done both for climate change alone and for the combined effects of climate change and enhanced CO, concentrations to explore the sensitivity of the agricultural system to the projected changes. The economic study did not address the issues of whether the physical and institutional changes required to accommodate increased demand for irrigated acreage are feasible or whether new crops would be introduced. The study did not consider changes in global agriculture.

Results

The estimates of Adams et al. (see Volume C) for total agricultural and irrigated acreage changes in the southern Great Plains States (Oklahoma and Texas only) are shown in Table 17-4. Agricultural land is estimated to decrease in the southern Great Plains in all scenarios, with and without the direct effects of CO_2. Decreases range from 4 to 22%. Irrigated acreage, on the other hand, increases in all scenarios, from 9 to 30%. This is because of increased stability of irrigated yields relative to dryland yields, and because of a rise in commodity prices that makes expansion of irrigation production economically feasible.

Implications

The results of the agricultural economics study imply that wheat and corn production may shift away from the southern Great Plains. This may weaken the economic base of many rural communities in the region and cause dislocations of rural populations. Uncertainties exist about adaptation in the region, such as substitution of more heat- and drought-tolerant varieties and crops. If irrigated acreage expands as predicted in the economic analysis, changes in capital requirements for agriculture would also occur.

If irrigated acreage does increase in the area, groundwater overdrafts also would be likely, along with associated increases in surface and groundwater pollution and other forms of environmental degradation. The current analysis did not address the issue of whether the physical and institutional changes required to accommodate such an increase in irrigated acreage are feasible.

Irrigation

Higher air temperatures cause increased evaporative demands, which largely govern crop water use and irrigation water requirements. The climate and crop production changes that might be associated with global warming in the southern Great Plains are likely to heighten farmer interest in irrigation, both because evapotranspiration may increase and because irrigated crops might obtain a larger economic advantage in a less favorable climate. Therefore, climate change impacts on irrigation water requirements were analyzed in more detail.

Study Design

Allen and Gichuki (see Volume C) evaluated the effects of climate change and reduced transpiration due to enhanced CO on crop irrigation water requirements in the Great Plains. They used an irrigation water requirement model to calculate daily soil moisture balances, evapotranspiration, and irrigation water requirements for corn, wheat, and alfalfa. The model employed the Penman-Monteith combination method to estimate crop evapotranspiration (Monteith, 1965). Four levels of potential direct effects of CO_2 on transpiration were simulated.

Limitations

Some uncertainty is embedded in the evapotranspiration and irrigation water requirement estimates owing to mismatching of weather profiles and crop characteristics. Also, this study assumed that alfalfa, corn, and wheat all would respond similarly to increased CO_2 (which may reduce transpiration), although published reports of experimental results show different responses among crops (see Rose, Volume C). The majority of results presented in this study assumed that crop varieties would not change, even though farmers may shift to crops more adapted to the changed climate.

Results

In general, modeled results showed that seasonal irrigation requirements for an area growing alfalfa, corn, and winter wheat in the Great Plains would increase by about 15% under the doubled CO p scenario. These results are based on averages of the two GCM doubled CO 2 scenarios and the likely occurrence of only moderate CO_2 induced decreases in transpiration.

Irrigation requirements were estimated to vary depending on the type of crop, changes in climatic factors, and variations in response to CO_2. The perennial crop alfalfa showed persistent increases in seasonal net irrigation water requirements (see Figure 17-6). These increases are driven primarily by higher temperatures, with less influence from stronger winds, greater solar radiation, and a longer growing season.

On the other hand, decreases in seasonal net irrigation requirements were estimated for the region's two most important crops, winter wheat and corn, in most areas, depending on the projected direct effects of CO_2 on transpiration. These water need decreases would be generally due to shorter crop growing periods caused by higher temperatures, which accelerate crop maturity. When crop varieties appropriate to the longer growing season were modeled, irrigation requirements for winter wheat were estimated to increase. Water requirements during peak irrigation periods (when plant growth and temperatures are greatest) increased in almost all cases (Figure 177). These results are consistent with results from the crop modeling study.

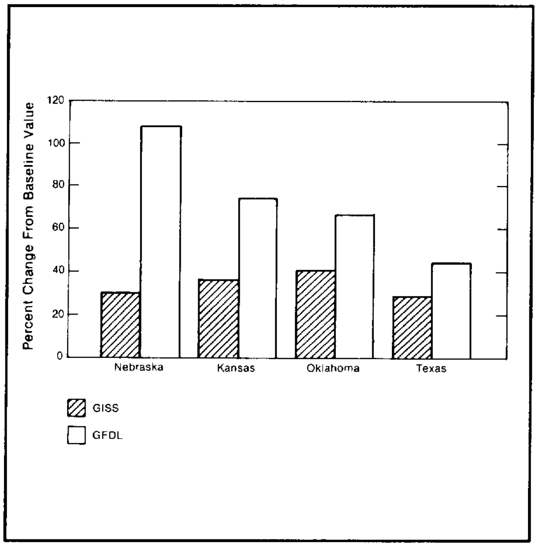


Figure 17-6. Seasonal irrigation water requirement for alfalfa for GISS and GFDL climate change scenarios and a moderate CO_2 induced decrease in transpiration (Allen and Gtchuki, Volume C).

Plant canopy (leaf) temperatures were estimated to increase above current baseline values for all crops and sites studied. Increases in leaf temperatures may reduce photosynthetic activity and crop yields. They also would make crops more sensitive to moisture stress. (See discussion on direct effects of CO_2 in Chapter 6: Agriculture.)

Implications

Any reduction in irrigation requirements for corn and winter wheat would be beneficial in the Great Plains because less water and energy would be required to produce the crops. However, the shortened crop growth periods might allow for double-cropping (planting two crops in one season), thus increasing total irrigation requirements. Farmers may shift to longer-season varieties, which would also increase water needs.

Expanded farm irrigation systems will require increased capital investments and larger peak drafts on groundwater systems and on energy supplies. Increased groundwater extraction could pose environmental and economic problems, especially where "water mining" is currently a major problem. Any action of irrigators to increase irrigation efficiency as an attempt to cope with projected water shortages, while economically beneficial, may lead to increased salinity problems if sufficient water is not applied to meet soil leaching requirements.

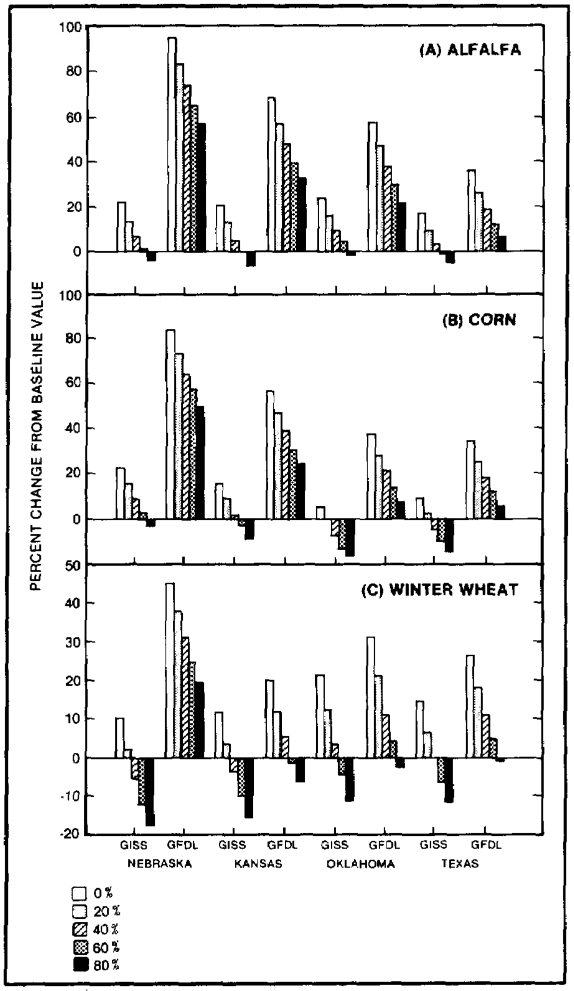


Figure 17-7. Percent change in net peak monthly irrigation requirement from baseline values for alfalfa, corn, and winter wheat for GISS and GFDL climate change scenarios and five levels of CO_2 induced decreases in transpiration (Allen and Gichuki, Volume C).

Water Quality

Agricultural pesticides are a high-priority pollution problem in at least half of the states within the US. Great Plains and Central Prairie. Potentially toxic agricultural chemicals can be removed from farmers' fields through degradation, surface runoff, sediment transport, and downward percolation. An understanding of potential climate change effects on the movements of agricultural chemicals is needed to identify potential changes in drinking water quality.

Study Design

Johnson et al. used the Pesticide Root Zone Model (PRZM) (Carsel et al., 1984) to simulate the partitioning of pesticides between plant uptake, chemical degradation, surface runoff, surface erosion, and soil leaching in the Great Plains under baseline climate and climate change scenarios. The locations modeled were representative of cropping practices for winter wheat and cotton in the region. The interactions among soil, tillage, management systems, pesticide transport, and climate change were studied. (For further discussion of the study's design and limitations, see Chapter 6: Agriculture.)

Results

As Figure 17-8 shows, surface runoff and surface erosion of agricultural pesticides increased under the GISS scenario for the winter wheat regions of the Great Plains. In the southern Great Plains cotton simulations, both the GISS and GFDL scenarios produced increases in surface pesticide losses with runoff and eroded soils.

The quantity of pesticides leached below the crop root zone is estimated to decrease everywhere except on silty soils in the cotton region. This overall decline most likely results from higher evaporative demands in response to temperature increases and to less available moisture for infiltration and deep percolation.

Implications

Results of the modeling imply that water quality in the southern Great Plains may be affected by climate change. However, because these results are highly dependent on the frequency and intensity of precipitation events, directions of change are uncertain. Surface water appears to be vulnerable to deterioration under climate change conditions, although the result does not hold for all cases. Groundwater quality in some areas appears to be less at risk than surface water quality. However, groundwater impacts will depend on total acres under production, application rates, soil type under cultivation, and changes in irrigated versus dryland acres.

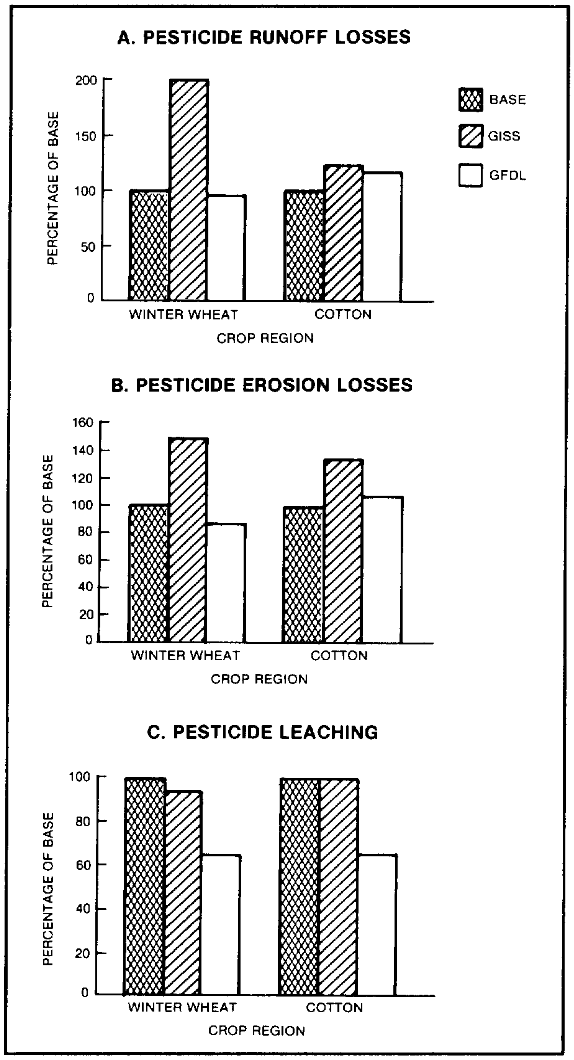


Figure 17-8. Regional summary of surface and subsurface pesticide loss as a percentage of the base climate scenario losses (Johnson et al., Volume C).

From a water quality perspective, decreased pesticide leaching may be advantageous. From a water quantity perspective, these results could be cause for concern. Less leaching can imply less water movement through soil profiles and less water availability for aquifer recharge. If water demands were to increase (as suggested by the crop production, economic, and irrigation analyses) at the same time that recharge rate decreased, competition for scarce water resources could increase dramatically in the region.

Livestock

Livestock production is a critical agricultural activity in the Great Plains and may be sensitive to climate fluctuations in several ways. The warming in the climate change scenarios may alleviate cold stress conditions in the winter but would exacerbate heat stress in the summer. Warmer summers are likely to necessitate more hours of indoor cooling. Reproductive capabilities have been shown to decline as a result of higher temperatures. Higher temperatures also may enable tropical diseases and pests to extend their ranges northward into the southern Great Plains. High temperatures also may reduce insect pest activities in some locations and increase them in others. (For a discussion of livestock issues, see Chapter 6: Agriculture.)

Schmidtmann and Miller (see Volume C) modeled the effect of climate warming on the horn fly, a common pest of pastured cattle that causes reductions in weight gain and milk production. (For a description of study design and limitations, see Chapter 6: Agriculture.) This study used only the GFDL scenario; since it had the highest temperatures, results should be considered as an extreme case. In Texas, horn fly populations were estimated to become lower in summer than they are currently because high temperatures are lethal to the insects when they are immature. Thus, weight gains of calves and feeder/stocker cattle could increase relative to current rates in Texas. In Nebraska, however, temperatures in the GFDL scenario would not reach lethal levels, and increases of 225 to 250 horn flies per head were estimated. This would result in greater weight reductions than those currently observed. These results suggest that greater stress may occur in livestock production in the northern part of the Great Plains, and that stress may be alleviated in Texas.

Stem et al. (see Volume C) studied the effects of climate change on animal disease patterns. (For study design and limitations, see Chapter 6: Agriculture.) The ranges of some diseases may be extended as habitats of disease vectors enlarge or as warmer environments permit longer seasonality of diseases currently present. Stem et al. calculated that the ranges of bluetongue and Rift Valley fever (both serious or potentially serious diseases of cattle) could be extended northward from Texas to Kansas and Nebraska with climate warming. Climate change thus has the potential to cause increased incidence of animal disease and to increase stress on livestock production in the Great Plains.

Electricity Demand

Linder and Inglis (see Volume H) estimated the changes in demand for electricity for the years 2010 and 2055. (For a description of the study's design and methodology, see Chapter 10: Electricity Demand.) In each case, they first estimated the change in electricity demand due to projected regional economic and population growth, and then factored in changes in demand based on the GISS transient climate change scenarios A and B. The results for the southern and central Great Plains are discussed here.

Results

Estimates of changes in peak demand, capacity requirements, and cumulative and annual costs projected for the climate change scenarios in the Great Plains are shown in Table 17-5. The results are driven by seasonal changes in weather-sensitive demands for electricity: summertime use for airconditioning and irrigation-pumping increases and outpaces reductions in demand for space heating in the winter. Electricity demand grows by 2 to 4% by 2010, and new capacity requirements are estimated to increase by 15 to 28% by 2010 for the climate change scenarios as compared with the base case (i.e., economic growth without climate change). By 2010, additional cumulative capital costs induced by climate change may be \$3.7 to \$6.7 billion, and annual costs of generating power may rise by 3 to 6%.

In 2055, new capacity generating requirements are estimated to increase by 22 to 45 gigawatts or 27 to 39%. Annual electricity demand in the region increased an additional 10 to 14% by 2055 under the climate

Table 17-5. Estimated Change in Peak Demand and Annual Energy Requirements Induced by Climate Change (%)

Utility area	2010				2055	
	GISS A		GISS B		GISS A	
	Ann.	Peak	Ann.	Peak	Ann.	Peak
Kansas/Nebraska	1.7	6.8	1.3	5.2	5.7	22.1
Oklahoma	3.0	7.9	2.8	6.6	11.3	25.3
Texas, east	3.0	7.9	2.8	6.6	11.3	25.3
Texas, south	3.3	10.0	1.7	5.1	10.6	24.6
Texas, west	3.1	8.6	2.4	6.1	11.1	25.1

Source: Linder and Inglis (Volume C).

change scenarios. New capacity requirements without climate change are estimated to be 20 GW by 2010 and 112 to 134 GW by 2055.

Linder and Inglis calculated that cumulative capital costs for electricity in the region would increase from $20 to $53 billion by 2055 with climate change. The estimated changes in annual costs induced by climate change range from $5 to $10 billion.

<u>Implications</u>

Increased electrical capacity requirements and the need to maintain the reliability of utility systems could place additional stress on the Great Plains. This is especially important if climate change increases the demand for irrigation, which is an important consumer of electricity in the region. Also, the potential exists for conflicts between power production and agriculture over the use of scarce resources such as water. Powerplants may take the cooling water they need from rivers or from the already overused Ogallala Aquifer, and increased coal and oil production in the region would utilize land that might be farmed. However, energy production may provide alternative income sources in an area whose economy is poorly diversified.

CLIMATE CHANGE AND THE OGALLALA AQUIFER

Warming and/or drying in the Great Plains may place greater demand on regional groundwater resources. Although the Ogallala Aquifer has come under close scrutiny in the past, it is important to note that previous studies have not addressed potential climate change impacts on this resource. Many of the problems associated with intense groundwater use (water depletion, soil damage, altered rural and farm economics, and potential reversion to dryland farming) could be exacerbated by global warming. This study shows that irrigated acreage in the Great Plains could increase and that the demand on the aquifer could rise by up to 15%. These potential adjustments to climate change should be studied to understand their implications for land use, resource conservation, regional economics, and community issues in the Ogallala area.

POLICY IMPLICATIONS

The policy options for responding, either in anticipation or in reaction, to climate change in the Great Plains range from noninterference, in which agricultural, water, and other resource systems are left to adjust without assistance, to a more active approach in which federal, state, and local government agencies plan for and assist in the process of adaptation.

Given the historical government involvement in agriculture, especially in this marginal region where support programs may mean the difference between farm survival and failure, it is likely that an active adjustment process will be called for. Policymakers in the Great Plains may have to respond to decreased agricultural production in the area, increased demand for water and electricity, poorer water quality, and changes in livestock production. The major issues that policymakers should address include land-use management, water resource management, and agricultural risk management (see Riebsame, Volume J). Regional utility planners and policymakers should also begin to consider climate change as a factor -- along with other uncertainties -- affecting their resource availability analyses and planning decisions.

Of course, uncertain and limited impact assessments such as those described above cannot be used to create and implement detailed policy. Rather, they should be viewed as scenarios that suggest the types of policies and the range of policy mechanisms and flexibilities that could alleviate potentially disruptive impacts from climate change. The eventual problem for the policymaker, of course, is deciding when to switch from scenario analysis to actual policy formulation and implementation. The last few sections of this chapter suggest some of the policy implications raised by the impacts described earlier.

Land-Use Management

Land managers should analyze how their missions and holdings may be affected by climate change and should develop flexible strategies to deal with potential impacts. Federal agencies, such as the Department of Agriculture, the Forest Service, the Fish and Wildlife Service, and the Department of Interior, should work with state agriculture, forest, and park agencies on such plans.

Climate change may cause agriculture and other land uses to become more environmentally and economically marginal in the Great Plains. Consequently, land uses may shift in intensity, type, and location. Indeed, locational shifts may involve several states or multiple regions. This adjustment process can be made more efficient and less disruptive if individual jurisdictions, such as municipalities, states, and federal regions, respond in a coordinated manner. Decisions made by managers of agriculture will affect forests, wildlife, and water resources. Decisionmakers should begin now to work together to develop a sound and flexible repertoire of anticipatory strategies; new institutional arrangements may be needed.

Some programs already in place can help to lessen the negative effects of climate change on the Great Plains. Federal legislation such as the "SodBuster Bill" and programs such as the Conservation Reserve Program are examples of new policies designed to reduce the use of marginal lands for agriculture. The basic goals of these laws are to protect the most erodible farmlands by removing them from crop production, and to use conservation as a tool for reducing overproduction. Such programs are prudent now for reducing erosion and may become even more important for protecting soil and water quality in a changing climate. However, protection of marginal lands may have to be weighed against the need for greater crop production if climate change lowers yields. For example, the government's response to the 1988 drought was to release some conservation land for cropping in 1989. This would help replenish food stocks but also would place a greater amount of marginal land at risk of erosion.

Water Resource Management

If GCM projections of climate change are qualitatively correct, parts of the Great Plains are likely to suffer increasing aridity. Farmers may demand more water for irrigation, although groundwater sources are already taxed. Competition for water resources between agricultural and nonagricultural demands may be exacerbated. Water managers need to factor the potential effects of climate change into their decisions on irrigation, drainage, and water transfer systems, and they should consider potential climate change as they formulate supply allocation rules, reservoir operating criteria, safety protocols, and plans for long-term water development. Water conservation techniques, water reallocation between competing uses, water transfers and marketing, and land-use adjustments should be evaluated for their ability to absorb the effects of a range of future climate changes. The goal at this point may not be to formulate detailed policy, but rather to test the climate sensitivity and feasibility of alternative water management policies and practices.

Decisionmakers should also consider the potential effects of climate change on water quality and the use of pesticides. They should examine alternative pest control strategies, such as Integrated Pest Management, which use biological control, genetic resistance, and innovative cropping systems to reduce pesticide applications.

Risk Management

Several government, semiprivate, and private institutions have a large financial stake in Great Plains agriculture through land credit, commodity and equipment loans, and insurance. Additionally, the federal government provides disaster relief for climate extremes affecting regional agriculture. Climate warming poses a potential long-term risk to the financial institutions supporting agriculture, to the resources available for emergency relief, and to individual farmers. This possibility should be carefully assessed, and plans should be made now to monitor risk as climate changes.

REFERENCES

Bowden, MJ., R.W. Kates, PA. Kay, W.E. Riebsame, D. Johnson, H. Gould, and D. Weiner. 1981. The effect of climate fluctuations on human populations: two hypotheses. In: Wigley, T.M.L., M.J. Ingram, and G. Farmer, eds. Climate and History. Cambridge, United Kingdom: Cambridge University Press, pp. 479-513.

Carsel, R.F., C.N. Smith, LA. Mulkey, J.D. Dean, and P. Jowise. 1984. Users' Manual for Pesticide Root Zone Model: PRZM. USEPA/ERL Report EPA-600-3-84-109. Washington, DC: U.S. Government Printing Office.

Dregne, H.E., W.O. Willis, and M.K. Adams. 1988. The metamorphosis of the "Great American Desert." Science of Food and Agriculture 6(11):27.

Glantz, M.H., and Ausubel, J.H. 1984. The Ogallala Aquifer and carbon dioxide: comparison and convergence. Environ. Conser. 11(2):123-31.

High Plains Associates. 1982. Six-State High PlainsOgallala Aquifer Regional Resources Study. Austin, TX.

Hurt, R.D. 1981. The Dust Bowl. Chicago: NelsonHall.

Jones, CA., and J.R. Kiniry. 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. College Station, TX: Texas A&M Press.

Liverman, D.M., W.H. Terjung, J.T. Hayes, and L.O. Mearns. 1986. Climatic change and grain corn yields in the North American Great Plains. Climatic Change 9:327-347.

Lockeretz, W. 1978. The lessons of the Dust Bowl. American Scientist 66:560-569.

Michaels, P.J. 1985. Economic and climatic factors in "acreage abandonment" over marginal cropland. Climatic Change 7:185-202.

Monteith, J.L. 1965. Radiation and crops. Experimental Agriculture Review 1(4):241-251.

Otter-Nacke, S., D.C. Goodwin, and J.T. Ritchie. 1986. Testing and Validating the CERES-Wheat Model in Diverse Environments. Houston, TX: Lyndon B. Johnson Space Center. AgRISTARS YM-15-00407. JSC 20244.

Popper, D.E., and FJ. Popper. 1987. The Great Plains: from dust to dust. Planning (December):1318.

Powers, W.L. 1987. The Ogallala's bounty evaporates. Science of Food and Agriculture 5(3):25.

Riebsame, W.E. 1983. Managing agricultural drought: the Great Plains experience. In: Platt, R., and G. Macinko, eds. Beyond the Urban Fringe: Land Use Issues in Non-Metropolitan America. Minneapolis: University of Minnesota Press, pp. 257-270.

Riebsame, W.E. 1987. Human Transformation of the United States Great Plains: Patterns and Causes. Proc. Symp. on the Earth as Transformed by Human Action, Clark University.

Ritchie, J.T., and S. Otter. 1985. Description and performance of CERES-Wheat: user-oriented wheat yield model. In: Willis, W.O., ed. ARS Wheat Yield Project. USDA-ARS. ARS-38. pp. 159-175.

Robertson, T., V.W. Benson, J.R. Williams, CA. Jones, and J.R. Kiniry. 1987. Impacts of climate change on yields and erosion for selected crops in the southern United States. In: Meo, M., ed. Proc. Symp. on Climate Change in the Southern U.S.: Impacts and Present Policy Issues, Science and Public Prog., Univ. of Oklahoma, Norman, OK.

Rosenzweig, C.1985. Potential CO_2-induced climate effects on North American wheat-producing regions.

Climatic Change 7:367-389.

Rosenzweig, C. 1987. Climate change impact on wheat: the case of the High Plains. In: Meo, M., ed. Proc. Symp. on Climate Change in the Southern U.S.: Impacts and Present Policy Issues, Science and Public Prog., Univ. of Oklahoma, Norman, OK.

Schneider, K. 1988. Drought cutting U.S. grain crop 31% this year. The New York Times August 12:A1.

Terjung, W.H., D.M. Liverman, and J.T. Hayes. 1984. Climatic change and water requirements for grain corn in the North American Great Plains. Climatic Change 6:193-220.

USDA. 1983. U.S. Department of Agriculture, U.S. Bureau of the Census. 1982 Census of Agriculture. Washington, DC: U.S. Government Printing Office.

USDA. 1985. U.S. Department of Agriculture, Economic Research Service. Foreign Agricultural Trade of the United States. Washington, DC: U.S. Government Printing Office.

Warrick, RA. 1984. The possible impacts on wheat production of a recurrence of the 1930s drought in the U.S. Great Plains. Climatic Change 6:5-26.

Warrick, RA. 1975. Assessment of Research on the Drought Hazard in the United States. Monograph No. 4. Boulder, CO: Natural Hazards Research and Applications Information Center, University of Colorado.

Warrick, RA., and M.J. Bowden. 1981. The changing impacts of drought in the Great Plains. In: Lawson, M.P., and M.E. Baker, eds. The Great Plains: Perspectives and Prospects. Lincoln: University of Nebraska Press, pp. 111-137.

Worster, D. 1979. Dust Bowl: The Southern Great Plains in the 1930s. New York: Oxford University Press.

CHAPTER 18
RESEARCH NEEDS

This report has suggested that concerns over the adaptability and fate of both natural and managed ecosystems in a changed climate are well founded. Natural forested ecosystems, aquatic and marine biota, wildlife in refuges, water quality in small lakes, and other resources may be vulnerable to rapid climate change. Strategies for mitigating changes in these systems are likely to be complex and difficult to implement. While it may be difficult to quantify the consequences, climate change may have large effects on biodiversity, primary productivity, and cycling of nutrients, and it may be difficult, if not impossible, to reverse these impacts.

This report has also shown that while intensively managed ecosystems, especially agroecosystems, may also be affected by a climate change, there seem to be more opportunities for human intervention to mitigate or adapt to their responses. Thus, the critically important question is whether the capacity for human intervention can keep pace with the rate of change induced by changing climate. Areas of major concern are the interactive effects of climate change and carbon dioxide increases on crop yields, and the adaptation rate of management practices.

Although it is clearly not possible to study all the potential effects of a change in the climate system, or to consider all the possible social or political ramifications of responding to climate change, there will be a continuing need to understand better the possible consequences of climate change because adaptation to different climates will be a necessary part of any complete societal strategies to cope with the greenhouse effect. Therefore, it is important to have in place a research framework for both the natural and the social sciences that will provide the information required to allow societies to respond to the challenge of large-scale, rapid changes in the climate system. This research should be undertaken simultaneously and in coordination with programs directed at establishing a broad consensus for governmental actions, both domestic and international, that address energy, land use, and other social policies that might lead to reduced emissions of greenhouse gases.

Research in the natural and social sciences must have an important role in developing wellreasoned adaptation strategies because it will provide the data and understanding of processes necessary to design efficient responses to a new climate, and better management techniques for the resources that must be conserved.

The needs of U.S. and international policymakers for information on the possible environmental effects of climate change and the processes that control them should not be underestimated, especially since the task of attempting to mitigate emissions of greenhouse gases is so large and complex. This chapter identifies some of the major topics for research in the natural and social sciences that should be pursued to help policy analysis and development in t1us area.

The scope of this chapter is necessarily broad. It addresses both the research proposed by EPA and the research recommendations of the scientific research community from a perspective that the development of sound environmental policy, both for mitigation and adaptation, depends on the capability of the scientific research community to respond to increasingly specific demands for information from policymakers.

RELATIONSHIP BETWEEN POLICY AND SCIENCE

Secretary of State James Baker and EPA Administrator William Reilly recently set forward four principles to guide policy development:

> The first is that we can probably not afford to wait until all of the uncertainties have been resolved before we do act. Time will not make the problem go away.

> The second is that while scientists refine the state of our knowledge, we should focus immediately on prudent steps that are already justified on grounds other than climate change. These include reducing CFC emissions, greater energy efficiency, and reforestation.
>
> The third is that whatever global solutions to global climate change are considered, they should be as specific and cost-effective as they can possibly be.
>
> The fourth is that those solutions will be most effective if they transcend the great fault line of our times, the need to reconcile the transcendent requirements for both economic development and a safe environment.

These four principles establish a framework within which both domestic and international programs will develop. They balance the needs for both scientific research and policy development, while clearly recognizing the international scope of the issue. In doing so, these four principles will act as the basis for U.S. participation in international assessment activities, as well as for domestic policy development.

The Global Climate Protection Act of 1987 directs EPA and the State Department to coordinate the development of national policy for global climate change. This coordination involves many other agencies with essential policy roles, such as the Department of Energy.

In addition, the Global Climate Protection Act directs EPA, in cooperation with other agencies, to prepare a scientific assessment of climate change. This assessment is now being coordinated through the Intergovernmental Panel on Climate Change, an organization created under the joint auspices of the United Nations Environment Programme and the World Meteorological Organization (WMO). It will be developed by a work group with extensive U.S. participation coordinated through the Federal Coordinating Committee on Science and Engineering Technology Committee on Earth Sciences. A second work group will analyze climate change impacts, and a third work group is responsible for examining response strategies. Each work group has approximately 18 months to develop an interim report. Reports from these three work groups will be critical to the development of international scientific and policy consensus on greenhouse issues.

EPA's domestic responsibilities, and the research reported on in this document, have led us to formulate several important questions that should be thought of as overriding themes, rather than as a list of all the potential issues:

- How rapidly might climate change as a result of future manmade emissions?
- What are the likely regional atmospheric manifestations of such global atmospheric changes?
- What are the likely extent and magnitude of ecological, environmental, and societal changes associated with a given change in regional atmospheres?
- What technologies and policy options exist to reduce the rate of growth in greenhouse gas emissions, and how much would they cost?
- What are the cultural and institutional barriers that might limit the implementation of such options?
- What are the likely consequences of proposed mitigative or adaptive policies?

These questions are viewed as the foundation for analyzing possible environmental changes due to climate change, and eventually for analyzing possible approaches to managing risks. They begin to match needs for policy development with scientific needs for understanding the functioning of the Earth as an integrated system. By doing so, they define the specific areas in which scientific research is necessary: biogeochemical dynamics, physical climate and the hydrologic cycle, ecosystem dynamics, Earth system history, and human interactions with the geosphere-biosphere. Indeed, they justify an overall program of research, with one of the main goals being to "establish the scientific basis for national and international policymaking related to natural and human-induced changes in the global earth system" (Federal Coordinating Committee on Science and Engineering Technology).

RESEARCH AND ASSESSMENT NEEDS IN THE SOCIAL SCIENCES

This report has identified many important issues that policy analysts and decisionmakers must begin or have begun to address. It is apparent that even for the heavily managed environmental resources such as agriculture and water supply, an existing range of concerns makes the response of resource managers to climate change difficult to predict. Even current climate variability is not always accounted for in resource management. Yet it is the response of resource managers and environmental policymakers to climate change that will ultimately determine how society responds to a changed climate both for managed and natural resources. The inadequacy of our current knowledge regarding how their decisions are made demands closer attention from the social science research community.

Institutional Response to Climate Variability and Climate Change

One of the major issues identified in t1us report is how institutions respond to current variability in climate. It is well known that current climate variability, represented by such episodes as the recurrence of the El Nino and periodic droughts, can have catastrophic effects on major regional industries, that in turn have larger, sometimes global consequences on supply and processing of resources. It is also well known that in both the relatively distant and relatively recent past, variability in climate has led to severe regional economic dislocation and subsequent migration of large numbers of people, even in industrialized societies such as the United States. What is not as well known is how the U.S. institutions responsible for managing agriculture, forestry, and water resources will be able to respond to future climate variability, especially if that variability increases. The drought of the summer of 1988 clearly illustrates that U.S. farms are still susceptible to severe weather conditions; it does not, however, answer the question of whether a succession of such droughts, as might be expected in future scenarios of a warmer, drier Grain Belt, could be accommodated by the existing government programs.

Water resource managers face similar problems. In California, all the scenarios indicated that large changes in the management of water might need to be considered if the snowpack were smaller and melted earlier. In the Great Lakes, lower water levels may necessitate changes in management. While changes in precipitation remain the most uncertain of the outputs from GCMs, the lessons for research in water management are relatively clear. We need to understand the degree to which there is flexibility in water allocation decisions, and to develop the information needed by water managers to evaluate possible changes in allocation under climate change.

In each of these cases, both the institutional and historical factors that affect the decisionmaking process must be analyzed and understood, as must local, regional, and national political influences. In particular, the problems of designing resource management systems for flexible response need to be addressed as institutional and investment questions. While the need for flexible resource management is clear, the reality of maintaining flexibility while still making decisions regarding large capital expenditures, such as building powerplants and dams, may be quite difficult. There will be a continued need to conduct targeted case studies of how resource managers currently consider climate variability and to address potential future changes in variability (see Chapter 19: Preparing for Climate Change).

In addition, while climate change may ultimately be one of the most important variables that managers must consider in the decisionmaking process, it may not be the most immediate. Research is necessary to show how devoting attention and resources to a developing issue such as climate change makes sense from a management and policy standpoint. Research is also necessary to examine the differences in how a wealthy, highly industrialized society, such as the United States, makes decisions about responding to climate variability and change and how other societies, especially lesser developed countries, make such decisions. Since climate change is intrinsically a global issue, such studies will be necessary to form a consensus regarding the need for coordinated responses and management strategies.

RESEARCH AND ASSESSMENT NEEDS IN THE NATURAL SCIENCES

As reviewed by the National Academy of Sciences Committee on Global Change (NRC, 1988), in order to be responsive to policy concerns, the primary scientific research needs are in those phenomena and processes that occur on global scales, or that occur on regional scales but will have global consequences over the next few decades to a few centuries. Therefore, research and assessment activities must examine global scale questions of emissions and atmospheric chemistry as well as the regional consequences of global atmospheric change. The transition from traditional disciplinary investigations of processes to interdisciplinary investigations of the links between processes on such large spatial scales will demand new approaches from the scientific research community.

Figure 18-1 represents in schematic fashion the information flow that must occur among scientific disciplines while explicitly taking into account the transitions between spatial scales. It indicates that the purpose of conducting research in emissions of trace gases, inventorying and evaluating the emission factors of anthropogenic and biogenic sources of trace gases, evaluating possible technological controls, investigating the possibility of positive feedbacks, and attempting to realistically simulate the emissions of trace gases is to provide information for understanding the composition of the atmosphere. Models can then be used to create estimates of atmospheric composition on approximately the same temporal and spatial scales.

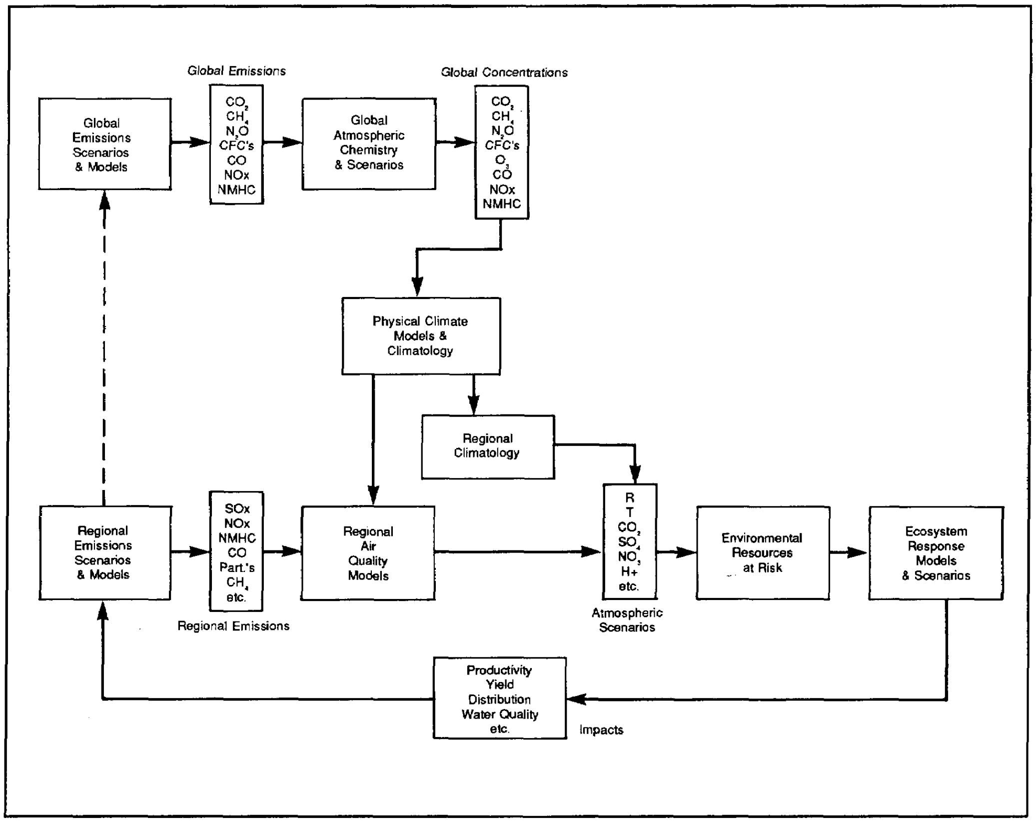


Figure 18-1. Relationship between global and regional information flow.

Climate System

The scientific research community should fully investigate the dynamic consequences of different compositions of the atmosphere, including the dynamics of the ocean as it influences both atmospheric composition and heat transfer. The derivation of regional climate scenarios from either modeling output or analog methods and scientific understanding are then necessary to link the processes on global scales with environmental and ecological research questions on regional and local scales. The climate system modeling community, as well as the statistical climatology community, must devote significant effort to improving the ability of the atmospheric sciences to make predictions on relatively small regional scales, so that policymakers can begin to have some quantitative confidence in the results from environmental and ecological modeling.

Research Scales

A further critical link identified in Figure 18-1 is that estimates of environmental changes will be needed on spatial scales that are larger than ecologists and environmental scientists have traditionally used in their research (e.g., ecoregions to biomes). While initially qualitative, as in much of this report, these estimates will be used both as input for assessments and as a way to formulate series of testable hypotheses concerning the processes that control projected ecological changes.

The ecological and environmental research community must, therefore, define those atmospheric variables that control the growth and distribution of major vegetation types, including crops, and must explore the physical and biological processes that control the distribution of water and nutrients in natural and managed landscapes. These definitions and processes must be those that affect the characteristics and dynamics of ecosystems on spatial scales commensurate with the atmospheric scales dermed above.

Socioeconomic Impacts

The final major link is between the ecological and environmental consequences of climate change and emissions of greenhouse gases. This link must include the interaction between societal impacts, such as changes in energy demand and end-use, and changes in emissions. It will be critical to establish interdisciplinary communication because of feedbacks between the biosphere and the atmosphere. Clearly, changes in the growth and distribution of major terrestrial vegetation types, as well as changes in ocean chemistry and biology, will alter biogenic emissions of trace gases. Of critical importance is the possibility that these biogenic emission changes may lead to even greater temperature changes (positive feedbacks), as has been hypothesized for methane. How climate change will affect anthropogenic emissions, and whether changes would be positive or negative feedbacks, is largely unexplored.

Data

Underlying all these concerns for the interaction among processes in the natural world is a critical need for long time-series of data on Earth system processes, and the information systems necessary to manage the data. No amount of modeling or experimentation of processes will replace actual observations of how the Earth system responds to changes in climate forcing and the degree and characteristics of its natural variability.

Objectives of Federal Global Change Program

Both the NAS (NRC, 1988) and the Federal Global Change Program (CES,1989) have identified the scientific elements intrinsic to understanding the Earth's behavior as an integrated system, and especially its response to global atmospheric change. The section below summarizes the scientific elements and their rationale, and presents the broad scientific objectives of the research to be sponsored in the Federal Global Change Program. These scientific elements refer directly back to the needs for information identified in Figure 18-1, as shown in Figure 18-2.

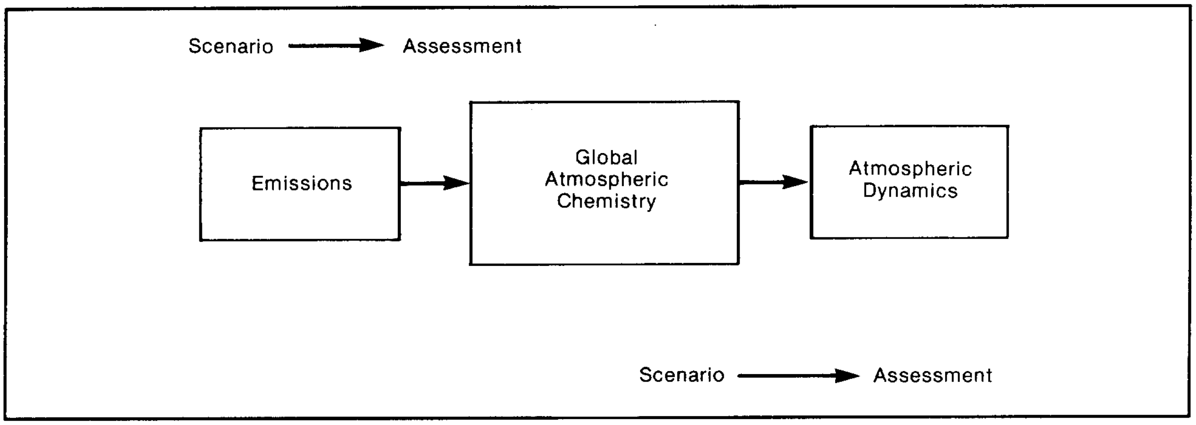


Figure 18-2. Two-stage scenario approach to integration.

- Biogeochemical dynamics include (1) the sources, sinks, fluxes, and interactions between biogeochemical constituents within the Earth system; (2) the cycling of biogeochemical elements in the atmosphere, oceans, terrestrial regions, biota, and sediments over Earth's history; and (3) the influence of biogeochemical elements on the regulation of ecological systems and contribution to potential greenhouse constituents (CO_2, CH_4, N_2O, CFCs) that have a direct influence on mate.

- Ecological systems and dynamics would involve the responses of ecological systems, both aquatic and terrestrial, to changes in global environmental conditions and of the influence of biological systems on the atmospheric, climatic, and oceanic systems. This includes studies of plant succession, terrestrial and aquatic biodiversity, extinctions, and relationships with geological substrate. Monitoring and specific ecosystem experiments can provide information on stresses influencing the biota and on the biotic response to natural and societal environmental stresses. Such information is needed to achieve the basic understanding required for the development of models. Identification and study of particularly sensitive ecosystems will be especially informative.

- Climatic and hydrologic systems would involve the study of the physical processes that govern the atmosphere, hydrosphere (oceans, surface and groundwaters, etc.), cryosphere (i.e., glaciers, snow), land surface, and biosphere.

These are clearly central to the description, understanding, and prediction of global climate change, particularly in terms of impacts on global climate conditions and the hydrologic system.

- Human interactions has been defined as the study of the impacts of changing global conditions on human activities. The global environment is a crucial determinant of humanity's capacity for continued and sustained development. Research should focus on the interface between human activities and natural processes.

- Earth system history is the study of the natural record of environmental change that is contained in the rocks, terrestrial and marine sediments, glaciers and ground ice, tree rings, eumorphic features (including the record of eustatic changes in sea level), and other direct or proxy documentation of past environmental conditions. These archive the Earth's history and document the evolution of life, past ecosystems, and human societies. Past ecological epochs with warmer or cooler climates relative to the present climate are of particular scientific interest.

- Solid-earth processes include the study of certain processes that affect the lifesupporting characteristics of the global environment, and especially the processes that take place at the interfaces between the Earth's surface and the atmosphere, hydrosphere, cryosphere, and biosphere. Solid-earth processes that directly affect the environment are of primary interest; processes that have only indirect effects are excluded.

- The solar influence is the study of the variability in solar radiation and its impact on atmospheric density, chemistry, dynamics, ionization, and climate. Research on the effects of solar variability on biogeochemical cycles as well as the impact of ultraviolet light on biology and chemistry would be particularly important here.

Of these scientific elements, studies of biogeochemical dynamics, climate and hydrologic systems, ecosystem dynamics, Earth system history, human interactions, and to a lesser extent, solar influences, are the most important from the standpoint of developing a policy-oriented research program. The degree to which the solid-earth processes are important depends entirely on their contribution to global change over the time-scale of a few decades to a few centuries. A better understanding of these processes remains an important scientific aspect of a Federal Global Change Program but can be anticipated to have less value from a public policy perspective.

Three Major Scientific Objectives

The scientific elements relevant to the development of well-informed public policy must be structured in a way that permits the overall objectives of the U.S. program to contribute to both scientific and policy communities. To accomplish this, the Federal Global Change Program has outlined three major objectives in its Strategy Document (CES, 1989).

1. Establish an integrated, comprehensive program for Earth system measurements on a global scale.

2. Conduct a program of focused studies to improve our understanding of the physical, chemical, and biological processes that influence Earth system changes and trends on global and regional scales.

3. Develop integrated conceptual and predictive Earth system models.

Each of these objectives simultaneously leads toward improving the monitoring, understanding, and predicting of global change. They aim to provide, by the year 2000, detailed assessments of the state of the knowledge of natural and humaninduced changes in the global Earth system and appropriate predictions on time scales 20 to 40 years into the future. Assessments of uncertainties in model outputs will be an integral part of these predictions.

THE ROLE OF EPA IN POLICY AND SCIENTIFIC RESEARCH

EPA's own activities have been structured to provide leadership in both policy analysis and development, as required by the Global Climate Protection Act, and in scientific research, especially on the consequences of changes in the climate system. The development of a broad-based, interdisciplinary scientific research program that responds to the policy-oriented questions identified earlier in this chapter has depended strongly on concurrent scientific planning efforts by the National Academy of Sciences and the Federal Global Climate Change Program.

Specifically, the goals and objectives of the EPA Global Climate Change Research Program have been structured to respond both to the policyoriented questions, and to the scientific needs identified by NAS in the U.S. proposal for the International Geosphere Biosphere Program and as adopted by the Federal Global Change Program. The program is designed to provide information on the biosphere and its response to climate change and technical information to develop policy options to limit and adapt to climate change. EPA's proposed research has two goals:

1. To assess the probability and magnitude of changes in the composition of the global atmosphere, the anthropogenic contributions to those changes, and the magnitude of subsequent impacts on the environment and

society.

2. To assess the likely extent, magnitude, and rate of regional environmental effects as a function of changes and variability in climate, for the purpose of evaluating the risks associated with changes in the climate system.

Eight associated scientific and institutional objectives have been identified:

1. To develop improved estimates for both anthropogenic and natural sources of radiatively important trace gases, and to investigate the feedback processes by which climate variability influences the sources of these gases.

2. To develop techniques for estimating current and future emissions of radiatively important trace gases.

3. To improve understanding of global atmospheric chemistry in order to project future concentrations of trace gases, including tropospheric ozone.

4. To relate global changes in climate to regional changes by constructing a series of regional atmospheric scenarios.

5. To predict ecosystems' responses to climate change and to test the processes that control those responses.

6. To document the spatial covariation of regional climate change with regional ecological change in order to establish comprehensive ecological monitoring in selected locations, cooperatively with EPA and other federal programs.

7. To develop information on technologies and practices that could limit greenhouse gases and to adapt to climate change.

8. To produce periodic scientific assessments in conjunction with other federal agencies and international research organizations, and to perform research to evaluate the consequences of adaptation and mitigation policies.

While defining the framework for EPA's own scientific research, these goals and objectives also assume that all federal agencies with significant policy responsibilities in issues of global climate change are going to be able to take advantage of developments in all areas previously discussed. Many of the developmental needs in the atmospheric and space sciences, and many of the global monitoring needs, will be beyond the capability of any one federal agency and will require the cooperation of all.

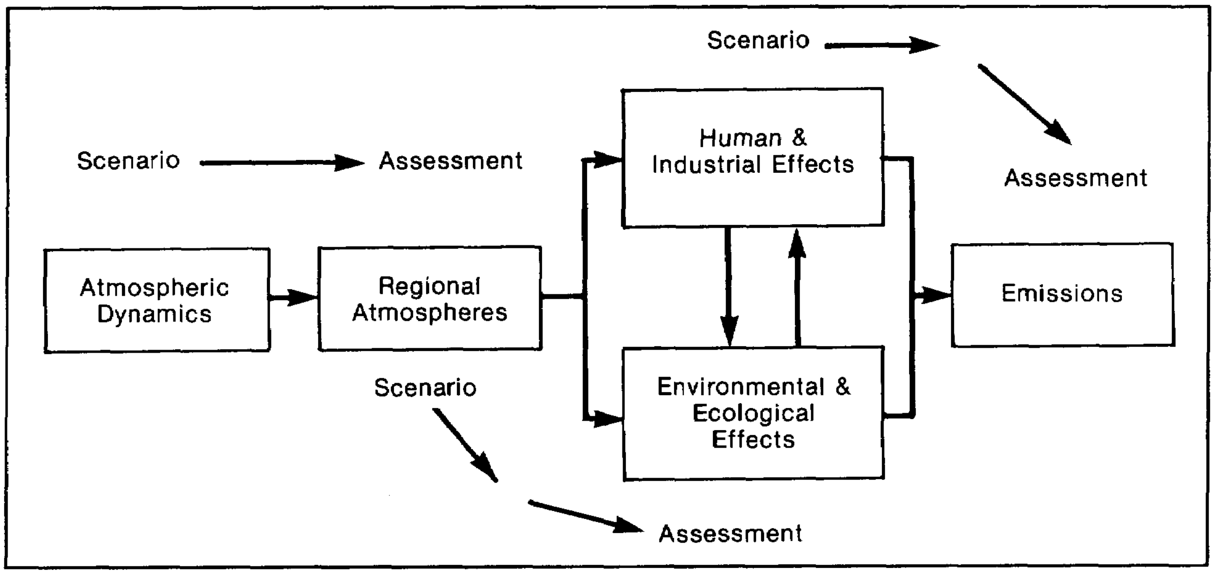
The goals and objectives of proposed policy research and activities in EPA closely follow the previously listed recommendations. The main foci will be on the development and coordination of a national policy, as called for in the Global Climate Protection Act, and the coordination and implementation of the International Response Strategies Assessment of the IPCC. Both mitigation and adaptation policies will be investigated, as outlined in the following chapter.

IMPACT ASSESSMENT METHODOLOGY

Continued efforts at assessing the causes and consequences of climate change are clearly needed. This report has illustrated one potentially valuable method for conducting such an assessment. However, because the need will continue, there is a corresponding need to consider how best to do assessments in a way that preserves both the understanding of what may happen and the certainty with which we know it. This section outlines the approach that will be taken in future impact assessment efforts led by EPA.

Integrated modeling of large-scale environmental issues has been attempted many times before and may be useful for policy analysis or for heuristic purposes. However, there is general agreement within the scientific community that a model adequate to simulate the dynamics of geophysical, chemical, and biological processes on global scales will be developed only after decades of research (ESSC, 1988).

Although achieving such a goal lies so far in the future, the question of how to deal with integrating diverse aspects of science in global climate change and its potential effects in the nearer term remains. One promising approach for integrating research results is to



treat the entire cycle of information flow (Figure 18-1) as a series of two-stage processes (Figures 18-2 and 18-3).

Figure 18-3. Three-stage approach to integration.

Within each two-stage process, research results should be treated as follows: The first part of the process is the creation of a set of scenarios, where a scenario is defined as a plausible combination of variables derived from a set of internally consistent assumptions. The second part of the process will evaluate the range of changes that are potentially attributable to each scenario and will evaluate the sensitivity of the underlying systems to different aspects of the scenarios. Thus, scenarios of changes in land use could be used to evaluate possible changes in emissions; scenarios of emissions could be used to evaluate the possible changes in atmospheric composition; scenarios of atmospheric composition could be used to evaluate changes in climate; climate scenarios could be used to evaluate the possible changes in ecosystems; and scenarios of ecosystem and land-use changes can in turn be used to evaluate possible changes in emissions.

The use of a scenario-assessment approach for impact assessments has several advantages. It could provide clear priorities for research on the sensitivities of important environmental processes in each scientific area. It maintains a realistically holistic view of the problems of global change, and it preserves information on the uncertainty of model results and data, in both qualitative and potentially quantitative fashion.

Each pair of scenario-response steps is explicitly decoupled from other pairs, while remaining consistent with them. Thus, such an approach can indicate both ranges and sensitivities of responses in potentially verifiable fashion within each pair, but does not attempt the premature task of modeling uncertainty all the way through the global system.

The use of scenarios as assessment and integrative tools is not part of the traditional scientific approach toward prediction and validation. Nevertheless, it is important from three standpoints:

- For scientific information to be of use to policymakers, a continued iterative process of evaluating the state of knowledge in the suite of sciences relevant to global change must be maintained. An iterative process of using and analyzing scenario-based assessments can provide such information in a usable and informative way.

- To achieve the multidisciplinary syntheses needed to make scientific advances in problems of global climate change, evaluation of the methods by which predictions are made and by which scenarios of change can be composed, and evaluation of the sensitivities of affected processes must continue. The scenario-based assessment approach provides a ready-made integrating framework for such continual evaluations.

- Because of the importance of this proposed research in public policy arenas, it is critical not to lose sight of what is and is not predictable. By distinguishing between a set of scenarios and actual verifiable predictions, the scenario-based approach can best illustrate the difference without becoming a morass of hedged bets.

REFERENCES

CES. 1989. Committee on Earth Sciences. Our Changing Planet: The FY 1990 Research Plan. The U.S. Global Change Research Program. A Report by the Committee on Earth Sciences. July 1989. Washington, DC: Executive Office of the President, Office of Science and Technology Policy. July.

ESSC. 1988. Earth Systems Science Committee. A Program for Global Change: Earth Systems Science a Closer View. Report of the Earth Systems Science Committee. Washington, DC: NASA Advisory Council. January.

IGBP. 1988. International Geosphere-Biosphere Program. Toward an Understanding of Global Change: Initial Priorities for the U.S. Contribution to the International Geosphere-Biosphere Program. Washington, DC: National Research Council, Committee on Global Change, National Academy Press.

CHAPTER 19
PREPARING FOR CLIMATE CHANGE

The preceding chapters suggest that a global warming could have significant impacts on farms and forests, rivers and lakes, fish and wildlife, and many practical aspects of everyday life. This issue is very different from other environmental problems. It is global in scope: all nations emit greenhouse gases and all will experience the impacts. Moreover, the changes are likely to last for centuries and could shape the very nature of society. Although many of the possible consequences may not occur for decades, it is important that we begin now to examine how we might respond.

The potential responses fall broadly into two categories: (1) limiting the change in climate; and (2) adapting to it. These two responses are complementary, not mutually exclusive. Because past emissions of greenhouse gases may eventually warm the Earth one degree Celsius, some adaptation will be necessary, and efforts to prepare for global warming can contribute information to the process of deciding whether, when, and how to limit it. On the other hand, slowing the rate of global warming would make it easier for humans and other species to adapt.

Although limiting climate change would require worldwide cooperation, responding to its consequences would not. Private citizens and companies can relocate or modify their operations. Communities and states can undertake public works or enact planning measures. Charitable foundations and profit-making corporations can support research to develop better response strategies. National governments can support all of these activities.

Preparing for global warming raises three challenges. First, the uncertainties make it difficult to be sure that we are employing the correct response: the climate may change more (or less) than anticipated; in the case of precipitation, we do not even know the direction of change. Second, the long-term nature increases the difficulty of forecasting the impacts and gaining the attention of decisionmakers more accustomed to focusing on near-term problems. Finally, adaptation would require thousands, perhaps millions, of decisionmakers to consciously consider global warming as they plan their activities.

These differences need not thwart the process of preparing for global warming. First, many types of institutions already cope with equally long-term and uncertain trends; transportation planners, for example, routinely consider economic growth over 30- to 50-year periods when picking routes for highways and urban rail systems. Second, reaching a consensus on what is fair would be easiest when no one feels immediately threatened. Finally, the decentralized nature of adaptation would enable the communities and corporations most sensitive to climate change to respond quickly, rather than having to await a national consensus on the most appropriate response.

Because a companion report ("Policy Options for Stabilizing Global Climate") examines options for limiting future global warming, this chapter focuses on adaptation strategies. We briefly discuss the process of choosing such strategies, then present several examples.

WHEN IS A RESPONSE WARRANTED?

Strategic Assessments

One of the most fundamental issues facing decisionmakers is whether to implement responses today or to defer preparation until the timing and magnitude of future climate change are more certain and the potential impacts are more imminent. Although global warming might eventually require particular actions, such actions need not necessarily be taken today. On the other hand, the likelihood of at least some global warming is sufficiently well established and the time required to develop a response sufficiently long that deferring all preparation could lead us to miss opportunities to substantially reduce the eventual economic and environmental costs of the greenhouse effect.

Individual organizations must decide for themselves whether or not to prepare for the greenhouse effect. The first question is whether global warming is likely to alter the success of current activities or projects now being planned. If not, preparing for the impacts of climate change usually would be unnecessary; if so, the next question is whether doing something today would be worthwhile.

We use the term "strategic assessment" to refer to the process by which people and organizations examine whether, when, and how to respond to global warming, based on what people know today. In some cases, these assessments formally consider the costs and benefits of alternative responses; in others, a qualitative analysis is sufficient to reach a conclusion.

Strategic assessments would be good investments for almost any organization whose activities are sensitive to climate or sea level and whose decisions have outcomes stretching over periods of 30 years or longer. In many cases, these studies can use existing analytical tools and consequently be relatively inexpensive. If they reveal that action today is worthwhile, the savings from such action may be orders of magnitude greater than the cost of the studies. Even if they show that no action is necessary, many organizations will find it useful to know that their projects are not vulnerable, and the studies would contribute to society's understanding of the impacts of global warming.

These assessments can be conducted as decision-oriented analyses (e.g., supplements to ongoing evaluations of proposed projects) or as special studies focusing on particular programs or particular problems; Table 19-1 lists examples of each type.

Decision-Oriented Assessments

The most cost-effective strategic assessments are those conducted as a routine part of the evaluation of ongoing projects. Because they are oriented toward a specific near-term decision, they are not likely to be ignored. Moreover, their cost is often minimal because they supplement existing studies and therefore have little overhead. For example, once a consultant has developed a hydrologic model for a levee or dam, examining the potential implications of climate change may require little more than a few additional computer simulations.

The Council on Environmental Quality has held public meetings on the possibility of requiring federal agencies to consider climate change in environmental impact statements. The rationale is that (1) if climate changes, the environmental impact of some federal projects may be different than the impact if the climate does not change; and (2) these assessments are an inexpensive way to increase our understanding of the potential implications of global warming. The Corps of Engineers has recently announced that it intends to estimate the impacts of sea level rise in future feasibility studies and environmental impact statements for coastal projects. (Baldwin, Volume J, discusses including climate change as a consideration in environmental impact statements.)

Program-Oriented Assessments

Agencies with many potentially vulnerable activities may need programwide assessments. In some cases, the combined impact of climate change can be summarized by a single variable, such as flood insurance claims. On the other hand, many agencies, such as the TVA, the Corps of Engineers, and EPA, have programs that face several impacts, each of which must be examined separately.

Problem-Oriented Assessments

These studies are sometimes necessary because project-oriented studies lack a mandate to examine broader implications. Utility companies, for example, may want to consider the implications of increased demand due to warmer temperatures. Moreover, problems that are explicitly the responsibility of no one while implicitly the responsibility of several different groups could be beyond the scope of program-oriented assessments. For example, the combined impact of farm closures and forest dieback raises land-use questions that would be outside the responsibility of any single organization.

Criteria for Choosing a Strategy

Strategic assessments can objectively identify the implications of climate change and possible responses, but picking the "best" response will sometimes be a subjective decision based on a number of criteria:

Table 19-1. Examples of Strategic Assessments

Decisionmaker	Question
Decision-Oriented	
Home buyers	Is the buyer willing to accept long-term risk of erosion and flooding?
Forestry companies	Are the appropriate species being planted? If so, when would a shift be necessary?
Utility companies	Is the size of a proposed powerplant optimal given projected climate change?
City engineers	Should new drainage facilities be designed with extra margin for sea level rise and possibly increased rainfall?
Water resources agencies	Is the dam designed properly? Would its benefits be different?
Federal agencies developing environmental impact statements	Would sea level rise or climate change significantly alter the environmental impacts of a project?
Program-Oriented	
Research directors	For which impacts can we develop a solution? What would be the costs of the research and the potential benefits of anticipated solutions?
Utility companies	Does system capacity need to be expanded? If not, when would expansion be necessary?
Flood insurance programs	By how much would insurance claims increase? Does expanding the program to include erosion increase the impact of climate change?
Agricultural planners	Do current farm programs help or hinder the adjustments climate change might require?
Public health agencies	Would climate change increase the incidence of malaria and other tropical diseases in the United States?
Air pollution regulatory agencies	Should current regulatory approaches be supplemented with incentive systems, new chemicals, or relocation policies?
Problem-Oriented	
Natural resource agencies	Do we need a program to aid the survival of forests and other terrestrial ecosystems?
Federal and state agencies	Which options would ensure long-term survival of Louisiana's coastal wetlands?
Wetland protection agencies	How do we ensure that wetlands can migrate at sea level?
Canada and the United States	How do we manage changes in levels of the Mississippi River and Great Lakes?
State coastal zone agencies and barrier island communities	Would the state provide necessary funds to hold back the sea on barrier islands? If not, would the town bear the cost of retreat? Are current erosion and flood programs consistent with long-term response?
Water resource agencies	What should be done to address increased salinity in estuaries?
Air pollution agencies	Will climate change alter the results of current air-pollution strategies?
Public utility commissions	Should power companies be building extra capacity for increased demand?

Flexibility: Is the strategy reasonable for the entire range of possible changes (including no change) in temperature, precipitation, and sea level?

Urgency: Would the strategy be successful if implemented today but fail if implementation were delayed 10 or 20 years?

Low Cost: Can the strategy be implemented with a negligible investment today?

Irreversibility: Would failure to adopt a strategy result in irreversible loss of a resource?

Consistency: Does the policy support other national, state, community, or private goals?

Economic Efficiency: Are the benefits greater than the costs?

Profitability: Does the investment provide a return greater than alternative investments, i.e., greater than the "discount rate"?

Political Feasibility: Is the strategy acceptable to the public?

Health and Safety: Would the proposed strategy increase or decrease the risk of disease or injury?

Legal and Administrative Feasibility: Can existing organizations implement the strategy under existing law?

Equity: Would implementing (or failing to implement) the strategy impose unfair costs on some regions or on a future generation?

Environmental Quality: Would the strategy maintain clean air and water or help natural systems survive?

Private versus Public Sector: Does the strategy minimize governmental interference with decisions best made by the private sector?

Unique or Critical Resources: Would the strategy protect against the risk of losing unique environmental or cultural resources?

The highest priorities would generally be actions that meet the criteria of flexibility, urgency, irreversibility, and low cost, because they inherently address the major obstacles encountered in preparing for global warming: (1) flexible policies meet the challenge of uncertainty because they are appropriate regardless of how the climate eventually changes; (2) although analytical techniques substantially discount the benefits of taking action sooner rather than later, delaying action is not a viable option when the urgency criterion is met; (3) irreversible losses can be avoided only by anticipating a problem; and (4) low-cost options are always easiest to implement.

Nevertheless, these responses would not always be sufficient to address the implications of climate change. More comprehensive solutions would often involve measures with more significant costs that might prove, in retrospect, to have been unnecessary if climate does not change as projected. The costs of not acting may still be great enough to justify such actions, but decisionmakers would have to carefully weigh the various tradeoffs.

To a large degree, the procedures for doing so have already been developed and applied. Most corporations and many government agencies conduct profitability or cost-benefit analyses. If the principal costs and benefits of a strategy can be quantified in monetary terms, economic theory provides a rigorous procedure for making tradeoffs between present and future costs, and for considering uncertainty, profitability, and most of the other criteria.

Nevertheless, subjective assessments are necessary when the impacts cannot be readily valued in monetary terms. Many decisionmakers do not feel comfortable with economic estimates of the value of a lost human life, unique cultural resource, or endangered species. Although economic theory provides a procedure (discounting) for comparing present and future costs, it provides less guidance on how much wealth and how many unsolved problems one generation should pass along to future generations. Although it provides tools for assessing risk and uncertainty, economic theory does not specify the extent to which society should be riskaverse. Because there is no objective formula for addressing these types of issues, responses are more likely to be based on intuitive judgment and on what is broadly acceptable to the public.

EXAMPLE RESPONSES FOR ADAPTING TO GLOBAL WARMING

This chapter presents a variety of example responses rather than a single integrated strategy because the process of adapting to climate change would be relatively decentralized. Although the various impacts would not be completely independent of each other, responses to one type of impact in one region generally could be implemented regardless of whether strategies are implemented to address other types of impacts in other regions. The need to protect California's water supplies, for example, would be largely independent of the impact of global warming on southeastern forests, midwestern agriculture, mid-Atlantic barrier islands, and the level of the Great Lakes.

For purposes of this discussion, approaches for adapting to global warming can be broadly divided into four categories, three of which require a response before the climate changes:

- No immediate action is necessary if least-cost solutions could be implemented using existing technology and institutions as the problem emerges.
- Anticipatory action is appropriate where taking concrete actions today would avert irreversible and expensive costs.
- Planning is appropriate where we do not need to physically change what we are doing immediately, but where we need to change the "rules of the game" now, so that people can respond to new information in a way that furthers social goals.
- Research and education are appropriate in cases where decades would be required to develop solutions and to train people to implement them, or where uncertainties must be reduced before the appropriate action can be identified.

We discuss each of these categories in turn.

No Immediate Action

The urgency of responding to climate change depends not only on the severity of a potential impact but also on the extent to which taking action today would diminish the ultimate cost of adaptation or allow us to avoid problems that would be unavoidable if we waited before taking action. Even where the impacts of climate change would be severe, if the solution to a problem is well defined and can be implemented quickly, or if no known solution would substantially mitigate the problem, immediate action is not necessary (although in the latter case, research may be appropriate). Two examples follow.

Reservoir Operation Rules

The decision rules that govern the timing and magnitudes of water releases are generally based on historic climate variability. For example, if the flood season is March to May and droughts are from July to September, reservoir managers typically lower the water levels by the end of February to ensure adequate flood control capacity, and they allow the levels to rise in June to ensure adequate water in case of a drought. If global warming advanced the flood season by one month, managers could eventually shift the schedule of water releases. But since such modifications could be implemented quickly, there is no advantage in modifying the schedule until the climate changes.

Choice of Crops

The differences among crops grown in various regions of the country result largely from differences in temperature and water availability. If the climate of one state gradually comes to resemble the climate currently experienced in another state, farmers in the former state may gradually begin to plant the crops currently grown in the latter. But there is no advantage in switclung crops today.

Anticipatory Action

Although many responses will not be necessary for a few decades, studies have identified a number of instances in which physical responses to global warming are appropriate even today. These circumstances fall broadly into two categories: (1) incorporating awareness of global warming into long-term projects that are already under way, where climate change must be addressed either now or not at all; and (2) taking actions today that, without climate change, would not be necessary until later, if at all.

Modifying Ongoing Projects to Consider Climate Change

The rationale for incorporating global warming into current decisions is that the outcome of projects initiated today will be altered by changes in temperature, rainfall, sea level, or other impacts of global warming. For many long-term projects, factoring climate change into the initial design is economically efficient because the failure to do so would risk premature failure of the project, while the cost of doing so would be only a few percent of the total project cost. Because consideration of global warming would also ensure that projects are adequate to address current climate variability and trends in sea level, such modifications may prove to be worthwhile investments even if the anticipated climate change does not occur, as described in the following examples. Thus, these actions can satisfy the criteria of flexibility, urgency, irreversibility, and low cost.

Street Drains

Consider the replacement of a century-old street drain. If designed for the current 5-year storm, such a system might be insufficient with a 10% increase in the severity of the design storm or a 1-foot rise in sea level, necessitating a completely new system long before the end of the project's useful life. On the other hand, installing slightly larger pipes to accommodate climate change might cost only an additional 5%. In such a case, designing for changes in climate might prove to be worthwhile if these changes occurred; even if they did not occur, benefits would be realized because the system would provide additional protection during the more severe 10-year storm. (For additional examples, see Chapter 7: Sea Level Rise, and Chapter 13: Urban Infrastructure.)

Commercial Forests

Because some commercial tree species live as long as 70 years before being harvested, consideration should be given to modifying the locations of commercial forests and types of species planted to account for global warming. For example, some types of Douglas-firs need at least a few weeks of cold winter temperatures to produce seeds. Forestry companies currently concentrate planting efforts at the mountain bases, from which logs can be most readily transported. However, if temperatures rise, the forests there may no longer produce young firs to replace the old. Thus, it might be reasonable to begin planting farther up the mountain or in a colder region of the country.

A shift from long-lived species vulnerable to climate change to species having less vulnerability or shorter growing cycles may also be appropriate. If two species are equally profitable today but one would fare much better if climate changed, shifting to the latter species would involve little risk and might substantially help long-term profits. Shifting to a species whose life cycle is only 20 years would enable harvests to take place before the climate changes enough to adversely affect growth, and would make it easier to respond to climate change as it occurs (see Chapter 5: Forests).

Undertaking New Projects Primarily Because of Future Climate Change

In a few cases, where authorities are already contemplating public works for which the economic justification is marginal, the prospect of climate change might encourage decisionmakers to proceed today with such projects. For example, a storm surge that almost flooded London during the 1950s led the Greater London Council to develop plans to build a movable barrier across the Thames River. Although many questioned whether the barrier was worth building, steadily rising flood levels (1 foot every 50 years for the past 5 centuries) convinced the technical advisory panel that the barrier would become necessary; once that eventuality was generally recognized, the consensus was that the project should go forward.

Constructing a project today solely because of the greenhouse effect requires more certainty than incorporating climate change into the design of a project that would be undertaken anyway, primarily for two reasons: (1) undertaking a new project requires the legislature or the board of directors to initiate major appropriations rather than approve small increases in the cost of a project already approved; and (2) because it is not motivated by the need to address current problems, the project can be delayed until there is more certainty. Even if decisionmakers are sufficiently certain of future impacts, they do not have to initiate the project today unless the time expected to pass before the impacts occur is not much greater than the time required to design, approve, and build the project intended to prevent those impacts. Thus, only nearterm impacts of global warming and those whose solution would take several decades to implement require remedial action today. Two examples follow.

River Deltas

The loss of wet and dry land in the Mississippi River Delta in coastal Louisiana is one example of how global warming could alter the timing of a project (see Chapter 16: Southeast). If current trends continue, most of the delta will be lost by 2100. But if sea level rise accelerates, this can occur as soon as 2050. The immediacy of the problem is greater than these years suggest, because the loss of land is steady. Assuming the additional loss of land to be proportional to sea level rise, half the delta could be lost by 2030, with some population centers threatened before then.

Whether or not sea level rise accelerates, the majority of the delta can survive in the long run only if society restores the natural process by which the Mississippi River once deposited almost all of its sediment in the wetlands. Because billions of dollars have been invested over the last 50 years in flood-control and navigation-maintenance projects that could be rendered ineffective, restoring natural sedimentation would cost billions of dollars and could take 20 years or longer. Because of the wide variety of interests that would be affected and the large number of options from which to choose, another 10 to 20 years could pass from the time the project was authorized until construction began.

Thus, if sea level rise accelerates according to current projections and a project were initiated today, about half of the delta would remain when the project was complete; however, if the project were authorized in the year 2000, 60 to 70% might be lost before it was complete. By contrast, if sea level rise does not accelerate, the two implementation dates might imply 25% and 35% losses of coastal wetlands.

Undertaking a project today satisfies the flexibility criterion, because even current trends imply that something eventually must be done. Because a failure to act soon could result in an irreversible loss of much of the delta, it also satisfies the urgency criterion.

Purchase of Land

Purchasing land could keep options open for water resource management and wetlands protection. In regions where climate becomes drier, additional reservoirs may become necessary. However, because accurate forecasts of regional climate change are not yet possible, water managers in most areas cannot yet be certain that they will need more dams. Even in areas such as California where dams will probably be required, these will not have to be built for decades. Nevertheless, it may make sense to purchase the necessary land today. Otherwise, the most suitable sites may be developed, making future reservoir construction more expensive and perhaps infeasible. A number of potential reservoir sites have been protected by creation of parks and recreation areas, such as Tocks Island National Park on the Delaware River.

Federal, state, and local governments often purchase land to prevent development from encroaching on important ecosystems. Particularly in cases where ecosystem slufts are predictable, such as the landward migration of coastal wetlands, it may be worthwhile to purchase today the land onto which threatened ecosystems are likely to migrate. Even where the shifts are not predictable, expanding the size of refuges could limit their vulnerability (see Chapter 8: Biodiversity).

Land purchases for protecting ecosystems have two important limitations. First, they would almost certainly be inadequate to address all the species migration that might be required by climate change: protecting coastal wetlands would require purchasing most of the nation's coastal lowlands, and many types of terrestrial species would have to shift by hundreds of miles. Second, land purchases do not handle uncertainty well: if temperatures, rainfall, or sea level change more than anticipated, the land purchased will eventually prove to be insufficient.

Planning: Changing the Rules of the Game

Although concrete action in response to climate change is necessary today for only a few types of problems, defining the "rules of the game" may now be appropriate for a much wider class of problems. Doing so increases flexibility: if climate changes, we are better prepared; if it does not change, preparation has cost us nothing. Another advantage of this type of long-range planning is that reaching a consensus on what is fair is easier when no one is immediately threatened. Moreover, such planning reduces risk to investors: although they still face uncertainty regarding the timing and magnitude of climate change, planning can prevent that uncertainty from being compounded by uncertainty regarding how the government will respond. Two examples in which changing the rules of the game might be appropriate follow.

Land Use

The potential consequences of global warming suggest that it may already be appropriate to guide development away from areas where it could conflict with future environmental quality or public safety. This can be done through master plans, laws and regulations, and revisions of ownership rights. Land use is generally regulated by local governments and planning commissions, with state governments also playing a role in some areas.

A primary rationale for most local land-use planning is that by themselves, real-estate markets do not always produce economically efficient or socially desirable outcomes, because people do not bear all the costs or reap all the benefits from their actions. The uses to which people put their property often can have significant impacts on other property owners and the environment. Because zoning and other land-use restrictions are usually implemented long before anyone would want to undertake the prohibited activities, people have time to plan their activities around the constraints. If people know the rules of the game well in advance, those who want the option of subdividing their property or clearing a forest buy land where these activities are permissible, and those who want property in an area where such activities will not take place buy land where the activities are prohibited. Thus, in the long run, planning helps maintain environmental quality while imposing few costs that individuals could not avoid by buying property elsewhere.

The institutional capabilities of planning are well suited for addressing environmental impacts of climate change when the direction of the impact is known. The example of coastal wetland loss (outside Louisiana) has been extensively examined in the literature; many of the same principles would also apply to shifts in forests, interior wetlands, changing water levels in the Great Lakes, and keeping land vacant for reservoirs.

A possible goal of land-use planning would be to ensure that development does not block migration of ecosystems or preclude construction of a dam. Without planning, the land could be vacated only by requiring abandonment with relatively little advance notice, which would require compensation (except for the case of coastal wetlands in states where property owners do not currently have the right to erect shore-protection structures). Planning measures can either prevent development through zoning (or purchase of land, discussed above), or set the basic social constraint that ecosystems will be able to migrate, while allowing the market to decide whether or not development should proceed given this constfaint.

Preventing Development: Zoning

The most common tools for directing land use are master plans and the zoning that results from them. Zoning to ensure that land is available for a dam would be similar to zoning to keep land available for a freeway. For protecting ecosystems, however, zoning has the same problem as land purchases: it has to be based on a particular assumption regarding how far the ecosystem will need to migrate; if temperature, rainfall, or sea level change more than expected, zoning provides only temporary protection.

Flexible Planning: Allowing the Market to Decide

The rationale for these mechanisms is that preventing development is inefficient; in some cases developing a property might be worthwhile even if it would subsequently have to be abandoned. Flexible planning has the desirable feature of minimizing governmental interference with private decisions. For example, the overall constraint of keeping natural shorelines is set by the government, but the market decides whether nearby property is still worth developing given that constraint. If the effects of climate change do not materialize, the government has not unnecessarily prevented development (satisfying the low-cost criterion). Most importantly, these measures do not require a precise determination of how much climate will change, and thus satisfy the flexibility criterion.

With this situation in mind, the State of Maine has recently issued regulations stating that structures would have to be removed to allow wetlands to migrate inland in response to sea level rise. South Carolina has recently enacted legislation to substantially curtail construction of bulkheads. Because these rules do not interfere with the use of property for the next several decades, they have a minimal impact on property values, and thus do not deprive people of their property. The major limitation of this approach is that it may be too flexible: if sea level rise begins to require a large-scale abandonment, a state or local government may find it difficult to resist pressure to repeal the rule.

An alternative that avoids the risk of backsliding is to modify conventions of property ownership. One example would be long-term leases that expire 50 to 100 years hence or when high tide rises above a property's elevation. This approach, which has been applied to Long Island, allows the market to explicitly incorporate its assessment of sea level rise into its valuation of the leases. Although leaseholders have requested no-cost extensions on their leases when they expire, local governments generally have found enforcing the provisions of leases easier than enforcing regulations requiring people to abandon property. Moreover, this approach can be implemented by the private sector; for example, a conservancy willing to lease the land back to developers for 99 years might be able to buy lowlands inexpensively (see Chapter 7: Sea Level Rise).

<u>Water Allocation</u>

Particularly in the Southwest, the nation's water supply infrastructure is guided by policies embedded in contracts and laws that prescribe who gets how much water. Many of these rules are not economically efficient; water is wasted because of rules that do not allow people with too much water to sell it to people with too little. The equity of these formulas is often sensitive to climate; during wet periods, everyone may receive plenty, but in dry periods some get enough while others get none.

To a large degree, the means by which the impact of climate change might be reduced are already being advocated to address current climate variability and potential supply shortages due to population growth. These measures include legalizing water markets; curtailing federal subsidies, which lead to waste by keeping prices artificially low; and modifying allocation formulas (see Chapter 9: Water Resources).

Nevertheless, the changes required by global warming maybe different in one crucial aspect: the effective date of any rule changes. Because the most severe changes in rainfall from the greenhouse effect may still be decades in the future, the problem can be addressed even if the effective date is not until 2020. This situation, however, may enhance the political feasibility of instituting a rational response today, since no one need be immediately threatened. By contrast, if planning is deferred another 20 years, the impacts of climate change may become too imminent for potential losers to agree to the necessary changes.

Research and Education: Increasing Our Understanding

Although a particular problem may not require solutions for a few decades, society should begin preparing now. In some cases, we are decades away from having viable solutions or the public awareness necessary to reach a consensus. We now examine two vehicles for expanding our knowledge: research and education.

<u>Research and Development</u>

Research and development expenditures can often be economically justified in cases where other responses cannot. Most of the impacts of climate change at least theoretically could be mitigated, but in many cases, effective solutions have not yet been developed. Like strategic assessments, research is as valuable as the savings it makes possible.

Research is also one of the major vehicles by which one generation improves life for succeeding generations. Even if the economic efficiency of taking action to mitigate impacts of climate change cannot be demonstrated, some policymakers might find it equitable for this generation to provide solutions to accompany the problems we pass on to the next generation.

Table 19-2lists a number of research questions and applications that would assist adaptation. However, for the most part, strategic assessments have not been undertaken to determine the cost and probability of developing solutions or the magnitude of potential

Table 19-2. Example Research Problems and Applications

Research problem	Application
Synergistic impacts of CO_2, climate change, and air pollution on plants	Shifts in mix of trees and crops, drought-tolerant crops
Shifts in habitats of birds, fish, and land animals	Restoration ecology: rebuilding ecosystems that are lost
Ability of wetlands and coral reefs to keep up with sea level changes	Mechanisms to accelerate vertical growth
Erosion of beaches due to climatology and sea level change	More efficient placement of sand when beaches are restored
Ability of alternative plant strains to tolerate harsh climate	Development of heat- and drought-resistant crops
Magnitude of changes in global sea level and regional climate	Development of integrated pest management programs and better background data for groundwater protection policies
Shifts in microorganisms that currently diminish water quality in tropical areas	Long-term water supply planning

savings that might result, so it is difficult to be certain that the research would benefit society. The most notable exception is improvement in estimates of future climate change; for virtually every impact examined in this report, the relevant decisionmakers have told EPA that improved climate projections are critical for developing responses. (For more details on necessary research, see Chapter 18: Research Needs.)

Education

Efforts to prepare for climate change can be only as enlightened as the people who must carry them out. Education will be a critical component of any effort to address the greenhouse effect because (1) decisiorunakers in various professions will need to routinely consider the implications of global warming; and (2) an informed citizenry will be necessary for the public to support the public policy and institutional changes that may be required. Governments will almost certainly have a major role.

To factor global warming into their decision processes, people will need information about changes in climate variables, the resulting effects, and techniques for mitigating the impacts. Federal and state agencies have already sponsored large conferences on sea level rise each year since 1983; coastal engineers and policymakers are increasingly considering accelerated sea level rise in land-use decisions and the design of public works. This process is now beginning to unfold in the fields of utility planning and water-resource management, and may emerge in other areas.

Because climate change could require major public policy initiatives, governments must explain the issue to the public at large so that the various options can be fully considered. To a large degree, the news media and school systems will be responsible for explaining the issue to people. Nevertheless, governments can support these institutions by sponsoring public meetings, issuing press releases, and perhaps most important, translating the results of its technical studies into brochures and reports that are accessible to reporters, teachers, and the general public.

AUTHORS

Joseph J. Bufalini	USEPA - Atmospheric Research and Exposure Assessment Laboratory -Research Triangle Park, North Carolina
Lauretta M. Burke	The Bruce Company
Margaret M. Daniel	The Bruce Company
Robert L. DeVelice	USEPA - Environmental Research Laboratory - Corvallis, Oregon
Eugene C. Durman	USEPA Office of Policy, Planning and Evaluation
Peter L. Finkelstein	USEPA - Atmospheric Research and Exposure Assessment Laboratory - Research Triangle Park, North Carolina
Anthony Janetos	USEPA - Office of Research and Development
Roy Jenne	National Center for Atmospheric Research
Ross A. Kiester	USEPA - Environmental Research Laboratory - Corvallis, Oregon
George A. King	USEPA - Environmental Research Laboratory - Corvallis, Oregon
Kenneth P. Linder	ICF, Inc.
Janice A. Longstreth	ICF, Inc.
Linda O. Mearns	National Center for Atmospheric Research
Ted R. Miller	The Urban Institute
Mark W. Mugler	Apogee Research, Inc.
Ronald P. Neilson	USEPA - Environmental Research Laboratory - Corvallis, Oregon
Alan Robock	University of Maryland
Cynthia Rosenzweig	Columbia University/Goddard Institute for Space Studies
William E. Riebsame	University of Colorado
Michael C. Rubino	Apogee Research, Inc.
Joel B. Smith	USEPA Office of Policy, Planning and Evaluation
Dennis A. Tirpak	USEPA Office of Policy, Planning and Evaluation
James G. Titus	USEPA Office of Policy, Planning and Evaluation
Jack K. Winjum	USEPA - Environmental Research Laboratory -Corvallis, Oregon
Robert C. Worrest	USEPA - Environmental Research Laboratory -Corvallis, Oregon

CONTRIBUTING INVESTIGATORS AND PROJECTS

Authors: Adams, Richard M., J. David Glyer, and Bruce A. McCarl
Institution: Oregon State University and Texas A & M University
Title: The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment.
Appendix: Volume C - Agriculture

Authors: Allen, Richard C., and Francis N. Gichuki
Institution: Utah State University
Title: Effects of Projected CO_2 Induced Climate Changes on Irrigation Water Requirements in the Great Plains States (Texas, Oklahoma, Kansas, and Nebraska).
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Author: Assel, Raymond, A.
Institution: Great Lakes Environment Research Laboratory
Title: Impact of Global Warming on Great Lakes Ice Cycles.
Appendix: Volume A - Water Resources

Author: Baldwin, Malcolm F.
Institution: Environmental Management Support, Inc.
Title: Applicability of Federal Long-Range Planning and Environmental Impact Statement Processes to Global Climate Change Issues.
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Authors: Blumberg, Alan F., and Dominic M. DiToro
Institution: HydroQual, Inc.
Title: The Effects of Climate Warming on Lake Erie Water Quality.
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Authors: Botkin, Daniel B., Robert A. Nisbet, and Tad E. Reynales
Institution: University of California, Santa Barbara
Title: Effects of Climate Change on Forests of the Great Lake States.
Appendix: Volume D - Forests

Authors: Byron, Earl R., Alan Jassby, and Charles R. Goldman
Institution: University of California, Davis
Title: The Effects of Global Climate Change on the Water Quality of Mountain Lakes and Streams.
Appendix: Volume E - Aquatic Resources

Authors: Changnon, Stanley A., Jr., Steven Leffler, and Robin Shealy
Institution: Illinois State Water Survey and University of Illinois
Title: Impacts of Extremes in Lake Michigan Levels Along Illinois Shorelines: Low Levels.
Appendix: Volume H - Infrastructure

Authors: Croley, Thomas E., II, and Holly C. Hartmann
Institution: Great Lakes Environment Research Laboratory
Title: Effects of Climate Changes on the Laurentian Great Lakes Levels.
Appendix: Volume A - Water Resources

Author: Davis, Owen K.

Institution: University of Arizona
Title: Ancient Analogs for Greenhouse Warming of Central California.
Appendix: Volume D - Forests

Author: Dudek, Daniel J.
Institution: Environmental Defense Fund
Title: Climate Change Impacts upon Agriculture and Resources: A Case Study of California.
Appendix: Volume C - Agriculture

Author: Easterling, William E.
Institution: Resources for the Future
Title: Farm-Level Adjustments by Illinois Corn Producers to Climate Change.
Appendix: Volume C - Agriculture

Authors: Glantz, Michael H., Barbara G. Brown, and Maria E. Krenz
Institution: National Center for Atmospheric Research
Title: Societal Responses to Regional Climate Change: Forecasting by Analogy.
Appendix: Volume J - Policy

Author: Haile, Daniel G.
Institution: U.S. Department of Agriculture, Agriculture Research Service - Gainesville
Title: Computer Simulation of the Effects of Changes in Weather Patterns on Vector-Borne Disease Transmission.
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Author: Hains, David K.
Institution: C.F. Hains, Hydrologist, Inc.
Title: Impacts of Global Warming on Runoff in the Upper Chattahoochee River Basin.
Appendix: Volume A - Water Resources

Authors: Johnson, Howard L., Ellen J. Cooter, and Robert J. Sladewski
Institution: University of Oklahoma
Title: Impacts of Climate Change on the Transport of Agricultural Chemicals Across the USA Great Plains and Central Prairie.
Appendix: Volume C - Agriculture

Authors: Josselyn, Michael, and John Callaway
Institution: San Francisco State University
Title: Ecological Effects of Global Climate Change: Wetland Resources of San Francisco Bay.
Appendix: Volume E - Aquatic Resources

Author: Kalkstein, Laurence S.
Institution: University of Delaware
Title: The Impact of CO 2 and Trace Gas-Induced Climate Changes upon Human Mortality.
Appendix: Volume G - Health

Authors: Keith, Virgil F., J. Carlos DeAvila, and Richard M. Willis
Institution: Engineering Computer Optecnomics, Inc.
Title: Effect of Climatic Change on Shipping within Lake Superior and Lake Erie.
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Author: Leatherman, Stephen P.
Institution: University of Maryland
Title: National Assessment of Beach Nourishment Requirements Associated with Accelerated Sea Level Rise.
Appendix: Volume B - Sea Level Rise

Authors: Lettenmaier, Dennis P., Thian Yew Gan, and David R. Dawdy
Institution: University of Washington
Title: Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin, California.
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Authors: Linder, Kenneth P., and Mark R. Inglis
Institution: ICF, Inc.
Title: The Potential Impacts of Climate Change on Regional and National Demands for Electricity.
Appendix: Volume H - Infrastructure

Author: Livingston, Robert J.
Institution: Florida State University
Title: Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration.
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Authors: Longstreth, Janice, and Joseph Wiseman
Institution: ICF/Clement Associates, Inc.
Title: The Potential Impact of Climate Change on Patterns of Infectious Disease in the United States.
Appendix: Volume G - Health

Authors: Magnuson, John J., David K. Hill, Henry A. Regier, John A. Holmes, J. Donald Meisner, and Brian J. Shuter
Institution: University of Wisconsin, University of Toronto, and Ontario Ministry of Natural Resources
Title: Potential Responses of Great Lakes Fishes and their Habitat to Global Climate Warming.
Appendix: Volume E - Aquatic Resources

Author: McCormick, Michael J.
Institution: Great Lakes Environment Research Laboratory
Title: Potential Climate Changes to the Lake Michigan Thermal Structure.
Appendix: Volume A - Water Resources

Authors: Mearns, Linda O., S.H. Schneider, S.L. Thompson, and L.R. McDaniel
Institution: National Center for Atmospheric Research
Title: Analysis of Climate Variability in General Circulation Models: Comparison with Observations and Changes in Variability in 2x CO_2 Experiments.
Appendix: Volume I - Variability

Authors: Meo, Mark, Thomas E. James, Jr., Steve Ballard, Lani L. Malysa, Robert E. Deyle, and Laura A. Wilson
Institution: University of Oklahoma
Title: Policy Implications of Global Climate Change Impacts upon the Tennessee Valley Authority Reservoir System, Apalachicola River, Estuary, and Bay, and South Florida.
Appendix: Volume J - Policy

Authors: Miller, Barbara A., and W. Gary Brock
Institution: Tennessee Valley Authority
Title: Potential Impacts of Climate Change on the Tennessee Valley Authority Reservoir System.
Appendix: Volume A - Water Resources

Authors: Morris, Ralph E., Mike W. Gery Mei-Kao Liu, Gary E. Moore, Christopher Daly, and Stanley M. Greenfield
Institution: Systems Applications, Inc.
Title: Sensitivity of a Regional Oxidant Model to Variations in Climate Parameters.
Appendix: Volume F - Air Quality

Authors: Overpeck, Jonathan T., and Patrick J. Bartlein
Institution: Lamont-Doherty Geological Observatory and University of Oregon
Title: Assessing the Response of Vegetation to Future Climate Change: Ecological Response Surfaces and Paleoecological Model Validation.
Appendix: Volume D - Forests

Authors: Park, Richard A., Manjit S. Trehan, Paul W. Mausel, and Robert C. Howe
Institution: Butler University and Indiana State University
Title: The Effects of Sea Level Rise on U.S. Coastal Wetlands.
Appendix: Volume B - Sea Level Rise

Authors: Peart, Robert M., James W. Jones, R. Bruce Curry, Ken Boote, and L. Hartwell Allen Jr.
Institution: University of Florida
Title: Impact of Climate Change on Crop Yield in the Southeastern USA: A Simulation Study.
Appendix: Volume C - Agriculture

Authors: Penner, Joyce E., Peter S. Connell, Donald J. Wuebbles, and Curtis C. Covey
Institution: Lawrence Livermore National Laboratory
Title: Climate Change and Its Interactions with Air Chemistry. Perspective and Research Needs.
Appendix: Volume F - Air Quality

Authors: Ray, Daniel K., Kurt N. Lindland, and William J. Brah
Institution: The Center for the Great Lakes
Title: Effects of Global Warming on the Great Lakes: The Implications for Policies and Institutions.
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Author: Riebsame, William E.
Institution: University of Colorado
Title: Climate Change Perceptions Among Natural Resource Decision-Makers: The Case of Water Supply Managers.
Appendix: Volume J - Policy

Authors: Riebsame, William E., and Jeffrey W. Jacobs
Institution: University of Colorado
Title: Climate Change and Water Resources in the Sacramento-San Joaquin Region of California: Policy Adjustment Options.
Appendix: Volume J - Policy

Authors: Rind, David, R. Goldberg, and R. Ruedy
Institution: Goddard Institute for Space Studies, Columbia University, and Sigma Data Service Corporation

Title: Change in Climate Variability in the 21st Century.
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Authors: Ritchie, Joe T., B.D. Baer, and T.Y. Chou
Institution: Michigan State University
Title: Effect of Global Climate Change on Agriculture: Great Lakes Region.
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Author: Rose, Elise
Institution: Consultant
Title: Direct (Physiological) Effects of Increasing CO_2 on Crop Plants and Their Interactions with Indirect (Climatic) Effects.
Appendix: Volume C - Agriculture

Author: Rosenzweig, Cynthia
Institution: Columbia University/Goddard Institute for Space Studies
Title: Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study.
Appendix: Volume C - Agriculture

Authors: Schmidtmann, Edward T., and JA. Miller
Institution: U.S. Department of Agriculture, Agriculture Research Service - Beltsville, Maryland
Title: Effect of Climatic Warming on Populations of the Horn Fly, with Associated Impact on Weight Gain and Milk Production in Cattle.
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Author: Schuh, G. Edward
Institution: University of Minnesota
Title: Agricultural Policies for Climate Changes Induced by Greenhouse Gases.
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Authors: Sheer, Daniel P., and Dean Randall
Institution: Water Resources Management Inc.
Title: Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the State of California and Atlanta, Georgia
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Authors: Stem, Edgar, Gregory A. Mertz, J. Dirck Strycker, and Monica Huppi
Institution: Tufts University
Title: Changing Animal Disease Patterns Induced by the Greenhouse Effect.
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Authors: Stinner, Benjamin R., Robin AJ. Taylor, Ronald B. Hammond, Foster F. Purrington, David A. McCartney, Nick Rodenhouse, and Gary Barrett
Institution: Ohio Agricultural Research and Development Center and Ohio State University
Title: Potential Effects of Climate Change on Plant-Pest Interactions.
Appendix: Volume C - Agriculture

Authors: Titus, James G., and Michael S. Greene
Institution: U.S. Environmental Protection Agency
Title: An Overview of the Nationwide Impacts of Sea Level Rise.

Appendix: Volume B - Sea Level Rise

Authors: Urban, Dean L., and Herman H. Sheer
Institution: University of Virginia
Title: Forest Response to Climate Change: A Simulation Study for Southeastern Forests.
Appendix: Volume D - Forests

Authors: Walker, Christopher J., Ted R. Miller, G. Thomas Kingsley, and William A. Hyman
Institution: The Urban Institute
Title: Impact of Global Climate Change on Urban Infrastructure.
Appendix: Volume H - Infrastructure

Authors: Weggel, J. Richard, Scott Brown, Juan Carlos Escajadillo, Patrick Breen, and Edward L. Doherty
Institution: Drexel University
Title: The Cost of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two Meter Rise in Mean Sea Level.
Appendix: Volume B - Sea Level Rise

Author: Williams, Philip B.
Institution: Philip Williams & Associates
Title: The Impacts of Climate Change on the Salinity of San Francisco Bay.
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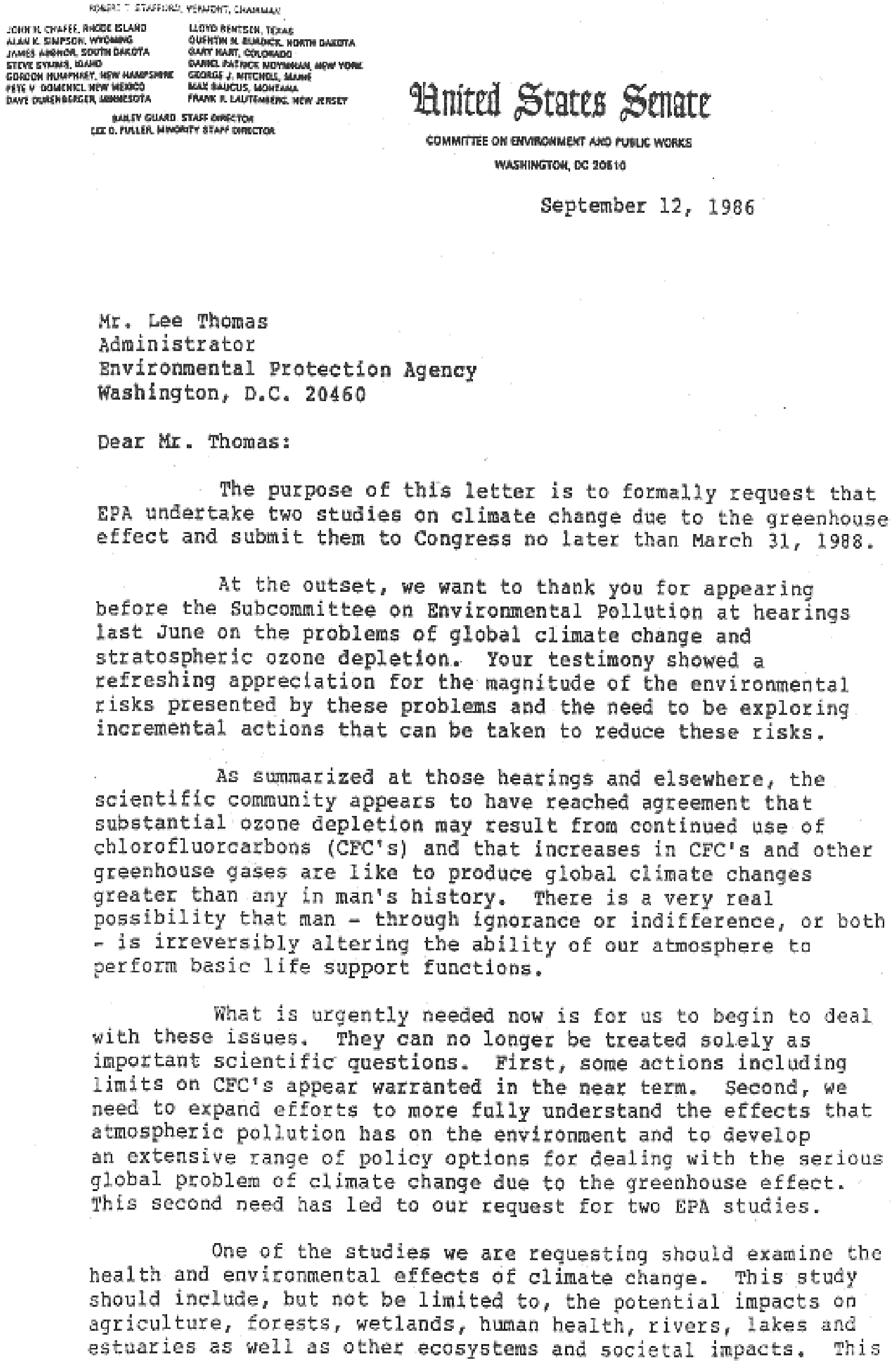
Authors: Woodman, James N., and Cari L. Sasser
Institution: North Carolina State University
Title: Potential Effects of Climate Change on U.S. Forests: Case Studies of California and the Southeast.
Appendix: Volume D - Forests

Author: Yohe, Gary W.
Institution: Wesleyan University
Title: The Cost of Not Holding Back the Sea: Phase 1, Economic Vulnerability.
Appendix: Volume B - Sea Level Rise

Authors: Zabinski, Catherine and Margaret B. Davis
Institution: University of Minnesota
Title: Hard Times Ahead for Great Lakes Forests: A Climate Threshold Model Predicts Responses to CO_2-Induced Climate Change.
Appendix: Volume D - Forests



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United States Senate

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS
WASHINGTON, DC 20510

September 12, 1986

Mr. Lee Thomas
Administrator
Environmental Protection Agency
Washington, D.C. 20460

Dear Mr. Thomas:

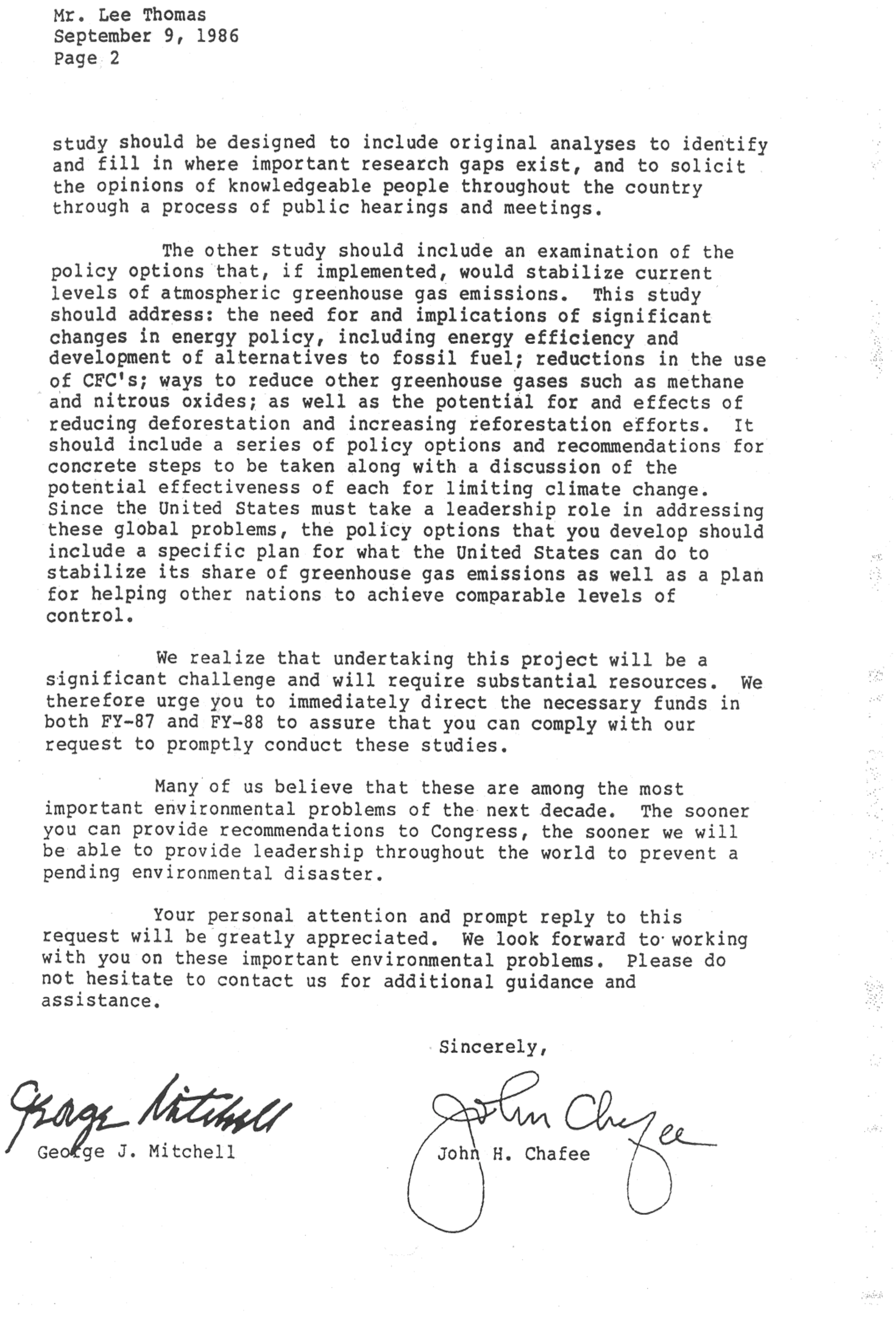
The purpose of this letter is to formally request that EPA undertake two studies on climate change due to the greenhouse effect and submit them to Congress no later than March 31, 1988.

At the outset, we want to thank you for appearing before the Subcommittee on Environmental Pollution at hearings last June on the problems of global climate change and stratospheric ozone depletion. Your testimony showed a refreshing appreciation for the magnitude of the environmental risks presented by these problems and the need to be exploring incremental actions that can be taken to reduce these risks.

As summarized at those hearings and elsewhere, the scientific community appears to have reached agreement that substantial ozone depletion may result from continued use of chlorofluorcarbons (CFC's) and that increases in CFC's and other greenhouse gases are like to produce global climate changes greater than any in man's history. There is a very real possibility that man - through ignorance or indifference, or both - is irreversibly altering the ability of our atmosphere to perform basic life support functions.

What is urgently needed now is for us to begin to deal with these issues. They can no longer be treated solely as important scientific questions. First, some actions including limits on CFC's appear warranted in the near term. Second, we need to expand efforts to more fully understand the effects that atmospheric pollution has on the environment and to develop an extensive range of policy options for dealing with the serious global problem of climate change due to the greenhouse effect. This second need has led to our request for two EPA studies.

One of the studies we are requesting should examine the 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



Mr. Lee Thomas
September 9, 1986
Page 2

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.

The other study should include an examination of the policy options that, if implemented, would stabilize current levels of atmospheric greenhouse gas emissions. This study should address: the need for and implications of significant changes in energy policy, including energy efficiency and development of alternatives to fossil fuel; reductions in the use of CFC's; ways to reduce other greenhouse gases such as methane and nitrous oxides; as well as the potential for and effects of reducing deforestation and increasing reforestation efforts. It should include a series of policy options and recommendations for concrete steps to be taken along with a discussion of the potential effectiveness of each for limiting climate change. Since the United States must take a leadership role in addressing these global problems, the policy options that you develop should include a specific plan for what the United States can do to stabilize its share of greenhouse gas emissions as well as a plan for helping other nations to achieve comparable levels of control.

We realize that undertaking this project will be a significant challenge and will require substantial resources. We therefore urge you to immediately direct the necessary funds in both FY-87 and FY-88 to assure that you can comply with our request to promptly conduct these studies.

Many of us believe that these are among the most important environmental problems of the next decade. The sooner you can provide recommendations to Congress, the sooner we will be able to provide leadership throughout the world to prevent a pending environmental disaster.

Your personal attention and prompt reply to this request will be greatly appreciated. We look forward to working with you on these important environmental problems. Please do not hesitate to contact us for additional guidance and assistance.

Sincerely,

George Mitchell
George J. Mitchell

John Chafee
John H. Chafee

Albert Gore

Max Baucus

Patrick J. Leahy

Robert T. Stafford

Dave Durenberger

Gordon J. Humphrey