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Volume 3: Climate Change

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EFFECTS OF CHANGES IN STRATOSPHERIC OZONE AND GLOBAL CLIMATE

Volume 3: Climate Change

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PREFACE

This document is part of a four volume report that examines the possible consequences of projected changes in stratospheric ozone and global climate resulting from emissions of chlorofluorocarbons, carbon dioxide, methane, and other gases released by human activities. In June 1986, the United Nations Environment Programme and the U.S. Environmental Protection Agency sponsored an International Conference on the Health and Environmental Effects of Ozone Modification and Climate Change, which was attended by scientists and officials, representing twenty-one countries from all areas of the world.

This volume examines the effects of the change in climate that might result from a global warming. Volume 1 of the proceedings provides an overview of the issues as well as the introductory remarks and reactions from top officials of the United Nations and the United States. Volumes 2 and 4 focus on the effects of ozone depletion and sea level rise.

This report does not present the official views of either the U.S. Environmental Protection Agency or the United Nations Environment Programme.

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Overview of the Effects of Changing the Atmosphere

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INTRODUCTION

Society is conducting a global experiment on the earth's atmosphere. Human activities are increasing the worldwide atmospheric concentrations of chlorofluorocarbons, carbon dioxide, methane, and several other gases. A growing body of scientific evidence suggests that if these trends continue, stratospheric ozone may decline and global temperature may rise. Because the ozone layer shields the earth's surface from damaging ultraviolet radiation (UV) future depletion could increase the incidence of skin cancer and other diseases, reduce crop yields, damage materials, and place additional stress on aquatic plants and animals. A global warming from the "greenhouse effect" could also threaten human health, crop yields, property, fish, and wildlife. Precipitation and storm patterns could change, and the level of the oceans could eventually rise.

To improve the world's understanding of these and other potential implications of global atmospheric changes, the United Nations Environment Programme (UNEP) and the U.S. Environmental Protection Agency (EPA) sponsored an International Conference on the Health and Environmental Effects of Ozone Modification and Climate Change during the week of June 16-20, 1986. The conference brought together over three hundred researchers and policy makers from approximately twenty nations. This four-volume report presents the seventy-three papers that were delivered at the conference by over eighty speakers, including two U.S. Senators, top officials from UNEP and EPA, some of the leading scientists investigating the implications of atmospheric change, and representatives from industry and environmental groups. Volume 1 presents a series of overview papers describing each of the major areas of research on the effects of atmospheric change, as well as policy assessments of these issues by well-known leaders in government, industry, and the environmental community. Volumes 2, 3, and 4 present the more specialized papers on the impacts of ozone modification, climate change, and sea level rise, respectively, and provide some of the latest research in these areas. This paper summarizes the entire four-volume report.

OZONE MODIFICATION

Atmospheric Processes

The ozone in the upper part of the atmosphere--known as the stratosphere--is created by ultraviolet radiation. Oxygen (O_2) is continuously converted to ozone (O_3) and back to O_2 by numerous photochemical reactions that take place in the stratosphere, as Stordal and Isaksen (Volume 1) describe. Chlorofluorocarbons and other gases released by human activities could alter the current balance of creative and destructive processes. Because CFCs are very stable compounds, they do not break up in the lower atmosphere (known as the troposphere). Instead, they slowly migrate to the stratosphere, where ultraviolet radiation breaks them down, releasing chlorine.

Chlorine acts as a catalyst to destroy ozone; it promotes reactions that destroy ozone without being consumed. A chlorine (Cl) atom reacts with ozone (O_3) to form ClO and O_2. The ClO later reacts with another O_3 to form two molecules of O_2, which releases the chlorine atom. Thus, two molecules of ozone are converted to three molecules of ordinary oxygen, and the chlorine is once again free to start the process. A single chlorine atom can destroy thousands of ozone molecules. Eventually, it returns to the troposphere, where it is rained out as hydrochloric acid.

Stordal and Isaksen point out that CFCs are not the only gas released by human activities that might alter the ozone balance. Increasing concentrations of methane in the troposphere increase the water vapor in the stratosphere, which helps create ozone. Carbon dioxide and other greenhouse gases (discussed below) warm the earth's surface but cool the upper atmosphere; cooler stratospheric temperatures slow the process of ozone depletion. Nitrous oxide (N_2O) reacts with both chlorine and ozone.

Stordal and Isakson present results of possible ozone depletion over time, using their two-dimensional atmospheric-chemistry model. Unlike one-dimensional models which provide changes in ozone in the global average, this model calculates changes for specific latitutdes and seasons. The results show that if concentrations of the relevant trace gases grow at recent levels, global average ozone depletion by 2030 would be 6.5 percent. However, countries in the higher latitudes (60°N) would experience 16 percent depletion during spring. Even in the case of constant CFC emissions, where global average depletion would be 2 percent by 2030, average depletion would be 8 percent in the high northern latitudes.

Watson (Volume 1) presents evidence that ozone has been changing recently more than atmospheric models had predicted. As Plate 1 shows, the ozone over Antarctica during the month of October appears to have declined over 40 percent in the last six to eight years. Watson also discusses observations from ozone monitors that suggest a 2 to 3 percent worldwide reduction in ozone in the upper portion of the stratosphere (thirty to forty kilometers above the surface), which is consistent with model predictions. Finally, he presents preliminary data showing a small decrease since 1978 in the total (column) ozone worldwide. However, he strongly emphasizes that the data have not yet been fully reviewed and that it is not possible to conclusively attribute observed ozone depletion to the gases released by human activities. While there are several hypotheses to explain why ozone concentrations have declined, none have been adequately established; nor did any of the atmospheric models predict the measured loss of ozone over Antarctica.

Ultraviolet Radiation

Many of the chemical reactions investigated by atmospheric scientists take place only in the stratosphere because they are caused by types of radiation only found in the upper atmosphere. As Frederick (Volume 1) explains, the sun emits radiation over a broad range of wavelengths, to which the human eye responds in the region from approximately 400 to 700 nanometers (nm). Wavelengths from 320 to 400 nm are known as UV-A; wavelengths from 280 to 320 nm are called UV-B, and wavelengths from 200 to 280 nm are known as UV-C.

Frederick explains why attention has primarily focused on the UV-B part of the spectrum. The atmosphere absorbs virtually all UV-C, and is expected to continue to do so under all foreseeable circumstances. On the other hand, UV-A is not absorbed by ozone.[1]. By contrast, UV-B is partially absorbed by ozone, and future depletion would reduce the effectiveness of this shield.

We now examine the potential implications of such changes on human health, plants, aquatic organisms, materials, and air pollution.

Effects on Human Health

The evidence suggests that solar ultraviolet radiation induces skin cancer, cataracts, suppression of the human immune response system, and (indirectly through immunosuppression) the development of some cutaneous infections, such as herpes. Emmett (Volume 1) discusses the absorption of UV radiation by human tissue and the mechanisms by which damage and repair may occur.

Emmett also examines UV radiation as the cause of aging of the skin and both basal and squamous skin cancers. In reviewing the role of UV radiation in melanoma (the most frequently fatal skin cancer), he states that some evidence suggests this link, but that currently there is no acceptable animal model that can be used to explore or validate this relationship. He concludes that future studies must focus on three major factors--exposure to solar radiation, individual susceptibility, and personal behavior. Waxler (Volume 1) presents evidence of a link between UV-B exposure and cataracts.

Volume 2 presents specific research results and provides more detail on many of the aspects covered in this volume. Scotto presents epidemiological evidence linking solar radiation with skin cancers, other than melanoma. His analysis suggests that Caucasians in the United States have a 12 to 30 percent chance of developing these cancers within their lifetimes, even without ozone depletion. Armstrong examines the role of UV-B exposure to melanoma in a study of 511 matched melanoma patients and control subjects in Western Australia. He shows that "intermittent exposure" to sunlight was closely associated with this type of cancer.

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[1] However, O_2 and N_2 reflect some UV-A back to space.

In a paper examining nonmelanoma skin cancer in Kuwait, Kollias and Baqer (Volume 2) show that despite the presence of protective pigmentation, 75 percent of cancers occur on the 10 percent of the skin exposed to sunlight. A second paper on skin cancer presents experimental evidence suggesting that the mechanism by which skin cancer could occur involves disruption of the cytoskeleton from exposure to UV-A and UV-B light (Zamansky and Chow, Volume 2).

The pathways by which suppression of the immune response might be triggered are explored in papers by DeFabo and Noonan, Daynes et al., and Elmets et al (all Volume 2). Davies and Forbes (Volume 2) show that mice exposed to UV-B radiation had a decrease in lifetime that was proportional to the quantity of radiation and not directly related to the incidence of skin cancer.

Possible implications of immune suppression of diseases and the mechanisms by which it occurs are still uncertain. However, several papers in Volume 2 suggest that in addition to skin cancer and contact hypersensitivity, diseases influenced by UV-B induced immune suppression include leishmaniasis and herpes infections. Fisher et. al (Volume 2) show that at least one sunscreen effectively protects mice exposed to UV-B radiation from sunburn; but it does not stop the immune suppression from interfering with a contact hypersensitivity (allergic) reaction.

Effects on Plants

The effects of increased exposure to UV-B radiation on plants has been a primary area of research for nearly a decade. Teramura (Volume 1) reports that of the two hundred plants tested for their sensitivity to UV-B radiation, over two-thirds reacted adversely; peas, beans, squash, melons, and cabbage appear to be the most sensitive. Given the complexities in this area of research, he warns that these results may be misleading. For example, most experiments have used growth chambers. Studies of plants in the field have shown them to be less sensitive to UV-B. Moreover, different cultivars of the same plant have shown very different degrees of sensitivity to UV-B radiation. Finally, Teramura suggests that potential effects from multiple stresses (e.g., UV-B exposure plus water stress or mineral deficiency) could substantially alter a plant's response to changes in UV-B alone.

In Volume 2, Teramura draws extensively from the results of his five years of field tests on soybeans. His data show that a 25 percent depletion in ozone could result in a 20 to 25 percent reduction in soybean yield and adverse impacts on the quality of that yield. Because soybeans are the fifth largest crop in the world, a reduction in yields could have serious consequences for world food supplies. However, some soybean cultivars appear to be less susceptible to UV-B radiation, which suggests that selective crop breeding might reduce future losses, if it does not increase vulnerability to other environmental stresses.

Bjorn (Volume 2) examines the mechanisms by which plant damage occurs. His research relates specific wavelengths with those aspects of plant growth that might be susceptible, including the destruction of chloroplast, DNA, or enzymes necessary for photosynthesis.

Aquatic Organisms

Aquatic plants would also be adversely affected by increased ultraviolet radiation. Worrest (Volume 1) points out that most of these plants, which are drifters (phytoplankton), spend much of their time near the surface of the water (the euphotic zone) and are therefore exposed to ultraviolet radiation. A reduction in their productivities would be important because these plants directly and indirectly provide the food for almost all fish. Furthermore, the larvae of many fish found in the euphotic zone would be directly affected, including crabs, shrimp, and anchovies. Worrest points out that fish account for 18 percent of the animal protein that people around the world consume, and 40 percent of the protein consumed in Asia.

An important question is the extent to which current UV-B levels are a constraint on aquatic organisms. Calkins and Blakefield (Volume 2) conclude that some species are already exposed to as much UV-B as they can tolerate. Thomson (Volume 2) shows that a 10 percent decrease in ozone could increase the number of abnormal larvae as much as 18 percent. In a study of anchovies, a 20 percent increase in UV-B radiation over a 15-day period caused the loss of all the larvae within a 10-meter mixed layer in April and August.

Many other factors could affect the magnitude of the impacts on specific species, ecosystems, and the food chain. An important mechanism by which species could adapt to higher UV-B incidence would be to reduce their exposure by moving further away from the water's surface during certain times of the day or year when exposure is greatest. Haeder (Volume 2) suggests, however, that for certain species such avoidance may be impaired by UV-B radiation.

Even for those organisms that could move to avoid exposure, unwanted consequences may result. Calkins and Blakefield present model results showing that movement by phytoplankton away from sunlight to reduce exposure to a 10 percent increase in UV-B would result in a 2.5 to 5 percent decrease in exposure to the photosynthetically active radiation on which their growth depends. Increased movement requires additional energy consumption, while changes in location may affect the availability of food for zooplankton, which could cause other changes in shifts in the aquatic food chain.

To a certain extent, losses within a particular species of plankton may be compensated by gains in other species. Although it is possible that no net change in productivity will occur, questions arise concerning the ecological impacts on species diversity and community composition (Kelly, Volume 1). Reductions in diversity may make populations more susceptible to changes in water temperatures, nutrient availability, diseases, or pollution. Changes in community composition could alter the protein content, dry weight, or overall food value of the initial stages of the aquatic food chain.

Polymer Degradation and Urban Smog

Current sunlight can cause paints to fade, transparent window glazing to yellow, and polymer automobile roofs to become chalky. These changes are likely to occur more in places closer to the equator where UV-B radiation is greater. They are all examples of degradation that could accelerate if depletion of the ozone layer occurs. Andrady and Horst (Volume 2) present a case study of the potential magnitude of loss due to increased exposure to

UV-B radiation on polyvinyl chloride (PVC). This chemical is used in outdoor applications where exposure to solar radiation occurs over a prolonged period. It is also used in the construction industry in siding and window frames and as a roofing membrane.

To analyze the potential economic impact of future ozone depletion on PVC, the authors assumed that the future service life of polymers would be maintained by increasing the quantity of light stabilizers (titanuim dioxide) used in the product. As a result, the costs associated with increased UV-B radiation would be roughly equal to the costs of increased stablizers. Preliminary results show that for a 26 percent depletion by 2075, the undiscounted costs would be $4.7 billion (1984 dollars).

Increased penetration of UV-B radiation to the earth's surface could play an important role in the formation of ground level oxidants (smog). UV-B affects smog formation through the photolysis of formaldehyde, from which radicals are the main source for deriving chain reactions that generate photochemical smog. Whitten and Gery (Volume 2) analyze the relationship between UV-B, smog, and warmer temperatures. The results of this preliminary study of Nashville, Philadelphia, and Los Angeles show that large depletions in stratospheric ozone and increases in temperature would increase smog by as much as 50 percent. In addition, because oxidants would form earlier in the day and closer to population centers (where emissions occur), risks from exposure could increase by an even higher percentage increase. Whitten and Gery also report a sensitive relationship between UV-B and hydrogen peroxide, an oxidant and precursor to acid rain.

CLIMATE CHANGE

The Greenhouse Effect

Concern about a possible global warming focuses largely on the same gases that may modify the stratospheric ozone: carbon dioxide, methane, CFCs, and nitrous oxide. The report of a recent conference convened by UNEP, the World Meteorological Organization, and the International Council of Scientific Unions concluded that if current trends in the emissions of these gases continue, the earth could warm a few degrees (C) in the next fifty years (Villach 1985). In the next century, the planet could warm as much as five degrees (NAS 1983), which would leave the planet warmer than at any time in the last two million years.

A planet's temperature is determined primarily by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which the atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then reradiates the heat as infrared radiation. However, water vapor, CO_2, and other gases in the atmosphere absorb some of the energy rather than allowing it to pass undeterred through the atmosphere to space. Because the atmosphere traps heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is commonly known as the "greenhouse effect." Without the greenhouse effect of the gases that occur naturally in the atmosphere, the earth would be approximately 33°C colder than it is currently (Hansen et al. 1984).

In recent decades, the concentrations of greenhouse gases have been increasing. Since the beginning of the industrial revolution, the combustion of fossil fuels, deforestation, and a few other activities have released enough CO_2 to raise atmospheric concentrations by 20 percent; concentrations have risen 8 percent since 1958 (Keeling, Bacastow, and Whorf 1982). More recently, Ramanathan et al. (1985) examined the greenhouse gases other than CO_2 (such as methane, CFCs, and nitrous oxide), and concluded that these other gases are likely to double the warming caused by CO_2 alone. Using these results, the Villach Conference estimated that an "effective doubling" of CO_2 is likely by 2030.[2]

Hansen et al. (Volume 1) and Manabe & Wetherald (Volume 1) present the results that their climate models predict for an effective doubling of CO_2. Both models consider a number of "climatic feedbacks" that could alter the warming that would directly result from CO_2 and other gases released by human activities. Warmer temperatures would allow the atmosphere to retain more water vapor, which is also a greenhouse gas, thereby resulting in additional warming. Ice and snow cover would retreat, causing sunlight that is now reflected by these bright surfaces to be absorbed instead, causing additional warming. Finally, a change in cloud cover might result, which could increase or decrease the projected warming. Although the two models differ in many ways, both conclude that an effective doubling of greenhouse gases would warm the earth's surface between two and four degrees (C).

Hansen et al. project the doubling to occur between 2020 and 2060. They also provide estimates of the implications of temperature changes for Washington, D.C., and seven other U.S. cities for the middle of the next century. For example, Washington would have 12 and 85 days per year above 38°C (100°F) and 32°C (90°F), respectively, compared with 1 and 35 days above those levels today. While evenings in which the thermometer fails to go below 27°C (80°F) occur less than once per year today in that city, they project that such evenings would occur 19 times per year. (See Plates 2 and 3 for worldwide maps of historical and projected temperature changes.)

Water Resources

Manabe and Wetherald (Volume 1) focus on the potential changes in precipitation patterns that might result from the greenhouse warming. They project substantial increases in summer dryness at the middle latitudes that currently support most of the world's agriculture. Their model also projects increased rainfall for late winter.

Beran (Volume 1) reviews the literature on the hydrological and water resource impacts of climate change. He expresses some surprise that only twenty-one papers could be found that address future water resource impacts. One of the problems, he notes, is that there is a better scientific understanding of how global average temperatures and rainfall might change, than for the changes that specific regions may experience. Nevertheless, he

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2 Studies on the greenhouse effect generally discuss the impacts of a carbon dioxide doubling. By "effective doubling" we refer to any combination of increases in concentrations of the various gases that causes a warming equal to the warming of a doubling of carbon dioxide alone.

demonstrates that useful information can be extracted by studying the implications of particular scenarios.

Nicholson (Volume 3) shows how historical changes in water availability have caused problems for society in the past. The best lesson of climatic history, she writes, "is that agricultural and economic systems must be flexible enough to adapt to changing conditions and, in the face of potential water scarcity, systems must be designed that require minimum use of resources." Wilhite (Volume 3) examines drought policies in Australia and the United States, concluding that the lack of national drought plans could substantially impair the ability of these two nations to successfully adapt to hydrologic changes resulting from the greenhouse warming.

Cohen (Volume 3) examines the potential implications of the global warming for water levels in the Great Lakes that separate Canada from the United States. Using results from the models of both Hansen et al. and Manabe & Wetherald, he concludes that lake levels could drop 10 to 30 centimeters. This drop would significantly reduce the capacity of ocean-going vessels that enter the Great Lakes. On the other hand, such a drop might be viewed as a benefit by the owners of critically eroding property whose homes are currently threatened by historically high lake levels. Street-Perrott et al. (Volume 3) discuss the historic impacts of changes in climate on the levels of lakes in North America, South America, Australia, and Africa.

Gleick (Volume 3) uses scenarios from the Hansen et al. and Manabe & Wetherald models (as well as a third developed by the National Center for Atmospheric Research) to drive a water-balance model of the Sacramento Basin in California. He finds that reductions in runoff could occur even in months where precipitation increases substantially, because of the increased rates of evaporation that take place at higher temperatures. He also points out that the models predict that changes in monthly runoff patterns will be far more dramatic than changes in annual averages. For seven of ten scenarios, soil moisture would be reduced every month of the year; for the other three cases, slight increases in moisture are projected for winter months. Mather (Volume 3) conducts a detailed analysis for southern Texas and northern Mexico; examines in less detail twelve regions around the world; and projects shifts in global vegetation zones.

Agriculture and Forestry

The greenhouse warming could affect agriculture by altering water availability, length of growing season, and the number of extremely hot days. Increased CO_2 concentrations could also have two direct impacts unrelated to climate change: At least the laboratory, plants grow faster (the CO_2 fertilization effect) and retain moisture more efficiently. The extent to which these beneficial effects offset the impacts of climate change will depend on the extent to which global warming is caused by CO_2 as opposed to other greenhouse gases, which do not have these positive impacts.

Parry (Volume 1) provides an overview of the potential impacts of climate change on agriculture and forestry. He points out that commercial farmers plan according to the average year, while family and subsistence farmers must ensure that even in the worst years they can make ends meet. Thus, the commercial farmer would be concerned about the impact of future climate change on average conditions and average yields, while farmers at the margin would be most concerned with changes in the probability of (for example) a severe drought that causes complete crop failure. Parry notes that the probability of two or more anomalous years in a row could create disproportionately greater problems for agriculture. For example, a persistent drought in the U.S. Great Plains from 1932 to 1937 contributed to about two hundred thousand farm bankruptcies.

Parry discusses a number of historical changes in climate. The Little Ice Age in western Europe (1500-1800 A.D.) resulted in the abandonment of about half the farms in Norway, an end to cultivation of cereals in Iceland, and some farmland in Scotland being permanently covered with snow. Concerning the late medieval cooling (1250-1500) he writes: "The failure to adapt to the changing circumstances is believed to explain much of the Norse decline. The Norse continued to emphasize stock-raising in the face of reduced capacity of the already limited pastures. The option of exploiting the rich seas around them, as the Inuit (Eskimos) successfully did, was not taken up . . . This is an extreme example of how governments can fail to identify and implement appropriate policies of response." It also suggests that effective responses can reduce damages from climate change.

The paper reviews a number of studies that project impacts of climate change on agriculture. "Warming appears to be detrimental to cereals in the core wheat-growing areas of North America and Europe." If no precipitation changes take place, a one-degree warming would decrease yields 1 to 9 percent while a two-degree (C) warming would decrease yields 3 to 17 percent. Parry also discusses how particular crop zones might shift. A doubling of CO_2 would substantially expand the wheat-growing area in Canada due to higher winter temperatures and increased rainfall. In Mexico, however, temperature stresses would increase, thereby reducing yields.

A number of studies have been conducted using the models of Hansen et al., Manabe & Wetherald, and others. Although these projections cannot be viewed as reliable forecasts, they do provide consistent scenarios that can be useful for examining vulnerability to climate change. Parry indicates that investigations of Canada, Finland, and the northern USSR using the model by Hansen et al. show reduced yields of spring-sown crops such as wheat, barley, and oats, due to increased moisture stress early in the growing period. However, switching to winter wheat or winter rye might reduce this stress. Parry goes on to outline numerous measures by which farmers might adapt to projected climate change.

Waggoner (Volume 3) points out that the global warming would not affect plants uniformly. Some are more drought-resistant than others, and some respond to higher CO_2 concentrations more vigorously than others. C_3 plants, such as wheat, respond to increased CO_2 more than C_4 plants such as maize. Thus, the CO_2 fertilization effect would not help the farmer growing C_4 crops accompanied by C_3 weeds. Waggoner also examines the impact of future climate change on average crop yields and pests, and the probability of successive drought years. He concludes that although projections of future changes are useful, historical evidence suggests that surprises may be in store, and that "agricultural scientists will be expected to aid rather than watch mankind's adaptation to an inexorable increase in CO_2 and its greenhouse effect."

The impact of future climate change on yields for spring wheat in Saskatchewan, Canada, is the subject of the paper by Stewart (Volume 3). Using the output from the Hansen et al. model (Volume 1), which projects that the effective doubling of carbon dioxide would increase average annual temperatures in that region by 4.7°C, he estimates that the growing season would start two or three weeks earlier and end three or four weeks later. Although average precipitation during the growing season would increase, he also finds that the area would become more prone to drought. The impact of climatic change would be to reduce yields 16 to 26 percent. Stewart estimates that the fertilization effect of a CO_2 doubling would reduce the losses to 6 to 15 percent. Cooter (Volume 3) examines the economic impact of projected climate change on the economy of Oklahoma, concluding that the Gross State Product would decline 75 to 300 million dollars. (The state's gross product in 1985 was approximately 50 billion dollars.)

Fritts (Volume 3) examines tree rings to assess how past changes in climate have affected forests, and concludes that tree rings are useful for estimating past changes in climate. Solomon and West (Volume 3) discuss the results of their efforts to model the future impacts. Considering the impact of climate change caused by doubled CO_2 without the fertilization effect, they find that "biomass (for boreal forests) declines for 50-75 years as warming kills off large boreal forest species, before new northern hardwoods can grow into the plot."

"Warming at the transition site causes an almost immediate response in declining biomass from dieback of mature trees, and in decline of tree mass as large trees die and are temporarily replaced by small young trees," they write. "The deciduous forest site . . . results in permanent loss of dense forest. One might expect the eventual appearance of subtropical forests similar to those in Florida today, but the real difficulty is the moisture balance (which is) more similar to those of treeless Texas today, than to those of southern Florida." Solomon and West go on to show how the fertilization effect from increased concentrations of CO_2 could offset part but not all of the drop in forest productivity.

Sea Level Rise

One of the most widely recognized consequences of a global warming would be a rise in sea level. As Titus (Volume 1) notes, global temperatures and sea level have fluctuated over periods of one hundred thousand years, with temperatures during ice ages being three to five degrees (C) lower and sea level over one hundred meters lower than today. By contrast, the last interglacial period (one hundred thousand years ago) was one or two degrees warmer than today, and sea level was five to seven meters higher.

The projected global warming could raise sea level by heating and thereby expanding ocean water, melting mountain glaciers, and by causing polar glaciers in Greenland and Antarctica to melt and possibly slide into the oceans. Thomas (Volume 4) presents new calculations of the possible contribution of Antarctica and combines them with previous estimates for the other sources, projecting that a worldwide rise in sea level of 90 to 170 centimeters by the year 2100 with 110 centimeters most likely. However, he also estimates that if the global warming is substantially delayed, the rise in sea level could be cut in half. Such a delay might result either from actions to curtail emissions or from the thermal lag induced by the oceans' ability to absorb heat.

On the other hand, Thomas also estimates that if a warming of four degrees results from a CO_2 doubling (which the model of Hansen et al. projects) and concentrations continue to grow after 2050, the rise could be as great as 2.3 meters. He also notes that an irreversible deglaciation of the West Antarctic Ice Sheet might begin in the next century, which would raise sea level another six meters in the following centuries.

Titus (Volume 1) notes that these projections imply that sea level could rise 30 centimeters by 2025, in addition to local subsidence trends that have been important in Taipei, Taiwan; Venice, Italy; the Nile Delta, Egypt; and most of the Atlantic and Gulf Coasts of the United States. The projected rise in sea level would inundate low-lying areas, destroy coastal marshes and swamps, erode shorelines, exacerbate coastal flooding, and increase the salinity of rivers, bays, and aquifers.

Bruun (Volume 4) argues that with a combination of coastal engineering and sound planning, society can meet the challenge of a rising sea. He discusses a number of engineering options, including dikes (levees) and seawalls, and adding sand to recreational beaches that are eroding, with a section on the battle that the Dutch have fought with the sea for over one thousand years. Goemans (Volume 4) describes the current approach of the Dutch for defending the shoreline, and estimates that the cost of raising their dikes for a one meter rise in sea level would be 10 billion guilders, which is less than 0.05 percent of their Gross National Product for a single year.

Goemans concludes that there is no need to anticipate such a rise because they could keep up with it. However, he is more concerned by the two-meter scenario: "Almost immediately after detection, actions would be required. It is not at all certain that decision-makers act that fast. . . . The present flood protection strategy came about only after the tragic disaster of 1953. When nobody can remember a specific disaster, it is extremely difficult to obtain consensus on countermeasures." For his own country, Goemans sees one positive impact: Referring to the unique experience of Dutch engineering firms in the battle with the sea, he suggests that "a rising sea may provide a new global market for this expertise." But he predicts that "the question of compensation payments may come up," for the poorer countries who did not cause climate change but must face its consequences.

Broadus et al. (Volume 4) examine two such countries in detail: Egypt and Bangladesh. The inhabited areas of both countries are river deltas, where low-lying land has been created by the sediment washing down major rivers. In the case of Egypt, the damming of the Nile has interrupted the sediment, and as the delta sinks, land is lost to the Mediterranean Sea. Broadus et al. estimate that a 50-centimeter rise in global sea level, when combined with subsidence and the loss of sediment, would result in the loss of 0.3 to 0.4 percent of the nation's land area; a 200-centimeter rise would flood 0.7 percent. However, because Egypt's population is concentrated in the low-lying areas, 16 and 21 percent of the nation's population currently reside in the areas that would be lost in the two scenarios.

The situation would be even more severe in Bangladesh. As Plate 4 shows, this nation, which is already overcrowded, would lose 12 to 28 percent of its total area, which currently houses 9 to 27 percent of its population. Moreover, floods could penetrate farther inland, which could leave the nation more vulnerable to the type of tropical storm that killed 300,000 people in the early 1970s, especially if the frequency of tropical storms doubled due to warmer water temperatures, which deSylva (Volume 4) projects. Broadus et al. conclude that the vulnerability of Bangladesh to a rise in sea level will depend in large measure on whether future water projects disrupt land-creating sediment washing down the Ganges.

Bird (Volume 4) examines the implications of sea level rise for other African and Asian nations, as well as Australia. While holding back the sea may be viable in Australia, he shows areas in New Guinea where people live in small cottages on the water's edge on a barrier island that almost certainly would be unable to justify construction of a dike. He also points to the Philippines, where many people have literally "taken to the water," living in small boats and maintaining fishing nets in their own plots of bay instead of land. Current wetlands, he suggests, may convert to these shallow bays, with people converting to a more water-based economy.

Leatherman (Volume 4) examines the implications of sea level rise for South America. He notes that such popular resorts as Copacabana Beach, Brazil; Punta del Este, Uruguay; and Mar del Plata, Argentina, are already suffering serious erosion. He concludes that because of the economic importance of resorts, governments will allocate the necessary funds to maintain their viability. However, he predicts that "coastal wetlands will receive benign neglect" and be lost.

Park et al. (Volume 4) focus on the expected drowning of coastal wetlands in the United States. Using a computer model of over 50 sites, they project that 40-75 percent of existing U.S. coastal wetlands could be lost by 2100. Although these losses could be reduced to 20-55 percent if new wetlands form inland as sea level rises, the necessary wetland creation would require existing developed areas to be vacated as sea level rises, even though property owners would frequently prefer to construct bulkheads to protect their property. Because coastal wetlands are important for many commerically important seafood species, as well as birds and furbearing animals, Park et al. conclude that even a one-meter rise in sea level would have major impacts on the coastal environment.

DeSylva (Volume 4) also examines the environmental implications of sea level rise, noting that in addition to wetlands being flooded, estuarine salinity would increase. Because 66 to 90 percent of U.S. fisheries depend on estuaries, he writes that these impacts could be important. He also suggests that coral reefs could become vulnerable because of sea level rise, increased temperatures, and the decrease in the pH (increased acidity) of the ocean.

Kuo (Volume 4) examines the implications of sea level rise for flooding in Taipei, Taiwan, and coastal drainage in general. Although Taipei is upstream from the sea, Kuo concludes that projected sea level rise would cause serious problems, especially because Taiwan is also sinking. He recommends that engineers around the world take "future sea level rise into consideration . . . to avoid designing a system that may become prematurely obsolete."

Gibbs (Volume 4) estimates that sea level rise could result in economic damages in Charleston, South Carolina, equal to as much as 25 percent of the annual product of the community. Anticipatory measures, however, could reduce these impacts by half. Gibbs finds that in some areas actions should be taken today, in spite of the current uncertainty regarding future rates of sea level rise, while for other areas it would be more prudent to wait until uncertainties are resolved.

Ken Smith, a realtor from coastal New Jersey, reacts to the other papers presented in Volume 4. He argues that the issue of sea level rise should be taken seriously today, but laments the fact that many of his fellow realtors make comments such as "What do you care? You won't be around to see it!" and the scientific community is "a bunch of eggheads who don't want us (to build on the coast) anyway." Smith suggests that part of the resistance to taking the issue seriously is that there are a number of "naturalists" who oppose building near the shore, and "most of the discussion seems to come from the 'naturalist' camp." Nevertheless, Smith argues that "the solutions--if there are any--should be contemplated now as part of a concerted global effort. This is a beautiful world, and we are its stewards."

Human Health and Ecological Impacts

Climate and weather have important impacts on human health. A global warming would increase the stresses due to heat, decrease those due to cold, and possibly enable some disease that require warm year-round temperatures to survive at higher latitudes. Kalkstein et al. (Volume 3) present a preliminary statistical assessment of the relationship of mortality rates to fluctuations in temperature in New York City. They find that a two to four degree (C) warming would substantially increase mortality rates in New York City, if nothing else changed. However, they caution that if New Yorkers are able to acclimatize to temperatures as well as people who currently live in U.S. cities to the south, fewer deaths would occur. Kalkstein et al. write that knowledgeable observers disagree about whether and how rapidly people adapt to higher temperatures; some people undoubtedly adjust more readily than others.

Although people may be able to adapt to changes in climate, other species on the planet would also be affected and may not be as able to control their habitats. Peters and Darling (Volume 3) examine the possibility that changes in climate would place multiple stresses on some species which would become extinct, resulting in a significant decline in biodiversity. (Mass extinctions appear to have accompanied rapid changes in temperatures in the past.)

Throughout the world reserves have been set aside where targeted species can remain relatively free of human intrusion. Peters and Darling ask: Will these reserves continue to serve the same function if the climate changes? In some cases, it will depend on whether the reserve's boundaries encompass areas to which plants and animals could migrate. Some species may be able to migrate "up the mountain" to find cooler temperatures; coastal wetlands could migrate inland. A northerly migration of terrestrial species would be possible in the undeveloped arctic regions of Alaska, Canada, and the Soviet Union; but human development would block migration of larger animals in many areas.

POLICY RESPONSES

Papers by UNEP Deputy Director Genady Golubev and EPA Administrator Lee Thomas (both in Volume 1) provide official views on the nature of the effects from projected changes in the atmosphere and the role of their institutions in addressing those changes. Golubev notes that while "the global issues are complex, uncertainty exceeds understanding, and patience is prudence," there is an other side to the story: "Our legacy to the future is an environment less benign than that inherited from our forbearers. The risks are sufficient to generate a collective concern that forebodes too much to wait out the quantifications of scientific research. Advocating patience is an invitation to be a spectator to our own destruction."

Golubev also points out that UNEP has worked for the achievement of the Vienna Convention for the Protection of the Ozone Layer, in which many nations have agreed to act in concert to address an environmental issue whose impacts have not yet been detected. Yet he notes that the agreement is for cooperation in research and does not yet bind nations to observe limits in production and emissions of gases that could deplete stratospheric ozone.

Thomas points out that both the potential depletion of ozone and the global warming from the greenhouse effect are examples of environmental problems that involve the "global commons." Because all nations contribute to the problem and experience the consequences, only an international agreement is likely to be effective. He urges scientists around the world to discuss this issue with their colleagues and key officials.

Richard Benedick, Deputy Assistant Secretary in the U.S. Department of State (Volume 1), describes the emerging international process addressing the ozone issue. Although the process for addressing climate change has not yet proceeded as far, he writes, "from my perspective as a career diplomat, it appears that the greenhouse effect has all the markings of becoming a high visibility foreign policy issue. . . . How we address this issue internationally depends to a great extent on our success or failure in dealing with the ozone depletion issue."

J.P. Bruce (Volume 1) of Environment Canada presents the issue of atmospheric change in the context of air pollution in general. He writes that ozone modification and climate change are "urgent issues," especially because important long-term decisions are being made today whose outcomes could be strongly affected by changes in climate and the ozone layer. Bruce recommends that emissions of CFCs be reduced, and concludes that "a new approach, a new ethic towards discharging wastes and chemical materials into the air we all breathe must soon be adopted on a international scale."

Two U.S. Senators also provide their reactions. John Chafee from Rhode Island (Volume 1) describes hearings that his Subcommittee on Environmental Pollution held June 10-11, 1986. "Why are policy makers demanding action before the scientists have resolved all of the questions and uncertainties?" he asks. "We are doing so because there is a very real possibility that society--through ignorance or indifference, or both--is irreversibly altering the ability of our atmosphere to perform basic life support functions for the planet." Albert Gore, Jr. from Tennessee, who has chaired three congressional hearings on the greenhouse effect, explains why he has introduced a bill in the U.S. Senate to establish an International Year of the Greenhouse Effect. "The legislations would coordinate and promote domestic and international research efforts on both the scientific and policy aspects of this problem, identify strategies to reduce the increase of carbon dioxide and trace gases, investigate ways to minimize the impact of the greenhouse effect, and establish long-term research plans." Senator Gore closes by quoting Sherwood Rowland (discussed below): "What's the use of having developed a science well enough to make predictions, if in the end all we're willing to do is stand around and wait for them to come true?" Both Senators call for immediate action to reduce global use of CFCs.

John S. Hoffman (Volume 1) emphasizes the inertia of the atmosphere and oceans. Because there are time lags between changes in emission rates, atmospheric concentrations, and changes in ozone and global warming temperatures, the types of management strategies must be different from those that are appropriate for controlling, for example, particulate pollution, where the problem goes away as soon as emissions are halted. CFC emissions would have to be cut 80 percent simply to keep concentrations from increasing. Although constant concentrations would prevent ozone depletion from worsening, Hoffman points out that even if we hold the concentrations of greenhouse gases constant once the earth has warmed one degree, the planet would warm another degree as the oceans come into equilibrium. Thus it might be impossible to prevent a substantial warming if we wait until a small warming has taken place.[3]

The final section of this volume presents the papers from the final day of the conference. Peter Usher of UNEP recounts the evolution of the ozone issue. Following Rowland and Molina's hypothesis that chlorofluorocarbons could cause a depletion of stratospheric ozone in 1974, UNEP held a conference in 1977 that led to a world plan of action to assess the issue and quantify risks. Since that time, UNEP has held numerous coordinating meetings leading up the the Vienna Convention. However, Usher suggests that motivating international effort on the greenhouse effect will be more difficult: "Prohibition of nonessential emissions of relatively small amounts (to control ozone depletion) is one thing, limiting emissions of carbon dioxide from coal- and oil-burning is quite another."

Dudek and Oppenheimer of the Environmental Defense Fund (U.S.) analyze some of the costs and benefits of controlling emissions of CFCs. They estimate that by holding emissions constant, 1.65 million cases of nonmelanoma skin cancers could be prevented worldwide, and that the cost of these controls would be 196 to 455 million dollars, depending on the availability of alternative chemicals.

Two former high-ranking environmental officials in the United States argue that we should be doing more to address these problems. John Topping recommends that CFCs in aerosol spray cans, egg cartons, fast-food containers, and other nonessential uses be phased out, and that people recognize that

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3 Titus (Volume 1) and Thomas (Volume 4) also explore inertia, noting that even if temperatures remained constant after warming somewhat, sea level would rise at an accelerated rate as the oceans, mountain glaciers, and ice sheets came into equilibrium with the new temperature.

along with energy conservation, nuclear power is the most likely alternative to fossil fuels over the next generation or two. He also recommends that society take steps to minimize the impacts of climate change and sea level rise, for example, by requiring environmental impact statements to consider the likely impacts.

Gus Speth, president of the World Resources Institute, recommends international efforts to stop tropical deforestation; a production cap for chlorofluorocarbons; increased energy conservation; advanced technologies for producing electricity from natural gas; and tighter regulations to limit carbon monoxide from automobiles, which would indirectly limit increases in atmospheric methane. He agrees with Topping that environmental impact statements for projects that could contribute to or be affected by climate change or ozone modification should consider these impacts.

Doniger and Wirth, from the Natural Resources Defense Council (U.S.), argue that the current uncertainties are no longer a reason to wait for additional information: "With the stakes so high, uncertainty is an even more powerful argument for taking early action." These authors conclude that sharp reductions in CFCs are necessary, pointing out that even with a production cap, atmospheric concentrations of these gases will continue to grow. Therefore, Doniger and Wirth propose an 80 percent cut in production over the next five years for CFCs 11 and 12, the halons, and perhaps some other compounds, with a complete phaseout in the next decade.

Richard Barnett of the Alliance for a Responsible CFC Policy (which represents CFC using industries) agrees that we should not delay all action until the effects of ozone depletion and climate change are felt; but he "would hardly characterize the activities over the last twelve years as 'wait and see' . . . The science, as we currently understand it, however, tells us that there is additional time in which to solidify international consensus. This must be done through discussion and negotiation, not through unilateral regulation."

Barnett adds that industry should "take precautionary measures while research and negotiations continue at the international level. We will continue to examine and adopt such prudent precautionary measures as recapturing, recycling, and recovery techniques to control CFC emissions; transition to existing alternative CFCs that are considered to be more environmentally acceptable; practices to replace existing systems at the expiration of their useful lives to equipment using other CFC formulations; practices in the field to prevent emissions where possible; encouragement of CFC users to look for processes or substances that are as efficient, safe, and productive--or better--than what is presently available."

Barnett concludes that "these environmental concerns are serious, but their successful resolution will require greater global cooperation in conducting the necessary research and monitoring, and in developing coordinated, effective, and equitable policy decisions for all nations."

We hope that this paper has provided the reader with a "road map" through the papers of this four-volume report on the potential effects of changing the atmosphere. But we have barely scratched the surface of each, just as the existing research has barely scratched the surface in discovering and demonstrating the possible risks of ozone modification and climate change. A continual evolution of our understanding will be necessary for our knowledge to stay ahead of the global experiment that society is conducting.

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FORESTRY, AGRICULTURE, AND ENDANGERED SPECIES

Atmospheric Carbon Dioxide Change: Agent of Future Forest Growth or Decline?

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ABSTRACT

Increasing concentrations of atmospheric CO_2 potentially could generate multiple and even opposing effects on forests. Greenhouse experiments have shown that enhanced CO_2 positively affects woody seedling growth, and that these effects may also occur in saplings and mature trees under elevated CO_2 concentrations. Yet, today's close geographic correspondence between certain climate variables and forest distributions suggests that climate changes resulting from future CO_2 increases could destroy many currently existing forests. The potential response of forests to these conflicting forces was examined using a computer model of tree growth and forest stand development. The model can incorporate simultaneous changes in CO_2 and climate, as well as the known responses of trees to these variables. The model was run with the annual modeled climate and CO_2 changes, suggested by current energy use projections, in three different ecosystems for several hundred simulated years. The results of these simulation experiments imply that the initial forest responses to changes in the environmental variables associated with increasing CO_2 may be minor because of tree longevity. In the long term, however, negative effects of climate change on forest growth may be strong enough to overwhelm the positive benefits derived from enhanced CO_2. Direct CO_2 benefits could, nevertheless, change the magnitude and the time required by forests to respond to climate change.

INTRODUCTION

The trace gas composition of the global atmosphere continues to change in response to natural causes, such as volcanic activity, and anthropogenic ones, such as fossil fuel use. The radiatively active gases (carbon dioxide, ozone, methane, water vapor, etc.) are of particular concern. For example, carbon dioxide is transparent to short wavelengths that compose the sunlight intercepted by clouds or the earth but not to the much longer wavelengths of infrared subsequently radiated back to the sky. A "greenhouse" effect occurs when some of this infrared radiation is absorbed by CO_2 and reradiated to earth, rather than to space.

The resulting CO_2-induced climate change should generate responses in forests. Many (but not all) trees and forest communities are now, or soon may be, subjected to a different and therefore more stressful climate than that to which they were adapted as germinating seeds (Solomon and West 1985). In addition, the change in CO_2 may directly affect plant growth and forests in that enhanced atmospheric CO_2 concentrations have increased the growth of tree seedlings in greenhouse and growth chamber experiments (Lemon 1983; Oechel and Strain 1985).

Lemon (1983) and Strain and Cure (1985) discussed the effects of enhanced CO_2 on photosynthesis, respiration, growth, and development of plants in greenhouse experiments. As yet, no research data indicate that mature trees growing in forests will be capable of taking advantage of the measured increases in dry matter production and in drought tolerance found in greenhouse herbs and woody seedlings.

Indeed, the opposite response (growth loss) could actually occur with enhanced atmospheric CO_2. Plants acclimate (cease to respond) to increased CO_2 concentrations after several days or months (Kramer and Sionit 1986; Oechel and Strain 1985), casting doubt on the long-term implications of short-term experiments with high CO_2 concentrations. Field studies measuring changes in tree growth in response to acidic precipitation and gaseous air pollutants revealed that annual tree growth has declined (Johnson 1983; McLaughlin, West, and Blasing 1983; Plochmann 1984), despite increases in global CO_2 of 25% to 30% since about 1850 (Solomon et al. 1985). Even the growth increases at very high altitudes (LaMarche et al. 1984), parallel with CO_2 increases, are ambiguous at best. For example, the timing of enhanced tree growth at these temperature-limited growth sites coincides more closely with the warming of the past century than with the CO_2 increases.

Forests will respond to changes in climate and CO_2 "fertilization," if at all, as a function of changing competitive advantages among species. Competition negates the simplistic view that all forest trees would benefit from increased CO_2. Instead, growth advantages conferred on one species must incur growth losses in less competitive species in a complex, but predictable, way. The discussion below represents our inital attempt to evaluate the importance of future conflicting and compensating forces which will operate on forests through the mechanism of interspecies competition.

APPROACHES TO ESTIMATING FOREST COMMUNITY RESPONSE TO ENVIRONMENTAL CHANGES

The most reliable approach to projecting the states of future atmospheric CO_2 and climate would be to wait for them to occur. Otherwise, a technique for projecting future changes is required. These projections will involve data from past and present environments, coupled with conceptual and mathematical models of the essential environmental, biological, and ecological processes involved in future events (see Reichle, Trabalka, and Solomon 1985). The models used to study the effects of climate and CO_2 on forests must consist of as much relevant knowledge as possible. The results of model trials will identify issues that require scientific research, by projecting the system behavior that would occur if our models faithfully represented the natural systems. There is no comprehensive, all-purpose model; there is, rather, a series of models and model approaches, each having strengths and weaknesses relative to the problems to which they are applied.

Two general model approaches are available for projecting the responses of forest trees to climate change alone, each based on different assumptions. The first is a pragmatic approach in which correlations among data sets, describing potential causes and effects, are substituted for knowledge of cause and effect processes. The present geographic distributions of climate variables are correlated with geographic distributions of biotic variables, such as the geography of ecosystems, communities, or densities of tree species. The expected future values of these climate variables can then be replaced directly with biotic variables (Emanuel, Shugart, and Stevenson, 1985; Solomon et al. 1984).

Unfortunately, empirical approaches are inherently incapable of characterizing the transient response patterns of forest ecosystems. The maximum life expectancy of trees of most species is of the same order of magnitude as the expected appearance of doubled CO_2 concentrations (Trabalka et al. 1985). Thus, the static forest ecosystems projected from empirical models probably will not be formed until many years after a climatic steady state is reached. The number of years involved and the nature of the transient forest ecosystems simply cannot be estimated using empirical projection techniques. Yet, the short-term (i.e., 100-200 years) transient responses are of most interest in any analysis of the anthropocentric climate impacts on forests (Solomon and West 1985).

Perhaps an even more telling deficiency in the empirical approaches is their inability to deal with carbon fertilization effects. The knowledge gained from greenhouse experiments on seedlings cannot be simply projected to populations or communities composed of adult trees, each competing for light and nutrients with other trees in the forest stand. To remedy these deficiencies, a very different approach is required.

This second approach uses simulation models of the cause-and-effect relationships (along with empirical relationships when cause and effect are unknown). The objective is to apply basic data and principles (i.e., tree-species natural histories, ecological and physiological processes, and environmental variables) to projections of the response of interacting and nonlinear ecosystems to climate change. Like the empirical approaches, simulations require estimates of future climate to drive the model experiments.

These models combine features of the mechanistic leaf models (scaled in minutes and millimeters) favored by physiologists (Oechel and Strain 1985) with the empirical spatial models (scaled in years and kilometers) favored by plant geographers (e.g., see Bartlein, Prentice, and Webb 1986). The models simulate tree responses that represent the summation of physiological processes, rather than dealing with the actual physiological processes underlying tree response to variables such as temperature, age, or moisture. The forest stand simulation approach (Shugart 1984) is particularly appropriate for examining potential carbon fertilization effects on forest stands, because the few experimental greenhouse data now available can be used to develop individual tree response functions (e.g., see Regehr, Bazzaz, and Boggess 1975, Figure 3).

Forest stand simulation models have been under development for the past fifteen years (JABOWA, Botkin, Janak, and Wallis 1972; FORET, Shugart, and West 1977, 1980). Adapting the models to assessing forest issues in the global CO_2 problem has required a long development period (Solomon et al. 1980, 1984; Solomon, West, and Solomon 1981; Solomon and Shugart 1984; Solomon and Tharp 1985; Solomon and Webb 1985; Solomon and West 1986; Solomon 1986). The concepts and biology incorporated into the latest versions of the model are described in detail by Shugart (1984) and Solomon et al. (1984). The mathematical expressions are provided by Shugart and West (1977) and Solomon and Shugart (1984). Regional variants of the FORET models have been tested on vegetation at several locations in the United States, Canada, and overseas (see Shugart 1984; Dale, Hemstrom, and Franklin, 1986; Solomon 1986). To supplement these studies of model validity in space, FORET has also been tested using long temporal sequences of 10,000 to 20,000 years for which there are fossil pollen records of actual forest composition (see Solomon and Webb 1985).

A diagram of the model structure is presented in Figure 1. In the idealized forest, growth of each tree species at each age (response function of diameter to time, center right) would occur at the greatest rates ever measured among forest-grown trees. However, such growth rarely occurs in the model because annual growth is reduced by extrinsic (warmth and moisture response functions, upper right) and intrinsic (stand density and shading response functions, lower right) limits to growth. New trees are added to simulated plots (establishment, lower left), and established trees are removed through increased probability of death due to slow growth (suppressed trees, center left) or by increased probability of death with age (mortality, upper left).

The foregoing describes the stand simulator used recently in climate effects studies that have not included CO_2 fertilization (Solomon and Shugart 1984; Solomon et al. 1984; Solomon and Tharp 1985; Solomon and West 1985; Solomon 1986). The results from some of these studies suggest the need to include direct CO_2 effects in simulation models (Solomon and West 1985). Modifications of the model to include fertilization effects of atmospheric CO2 would involve changes that might resemble those shown as dotted lines in Figure 1. The optimum growth with added CO_2 (center right) would increase at all ages, coincidentally enhancing the maximum age each species could attain and thereby reducing rates of mortality (center left). The complex of growth effects attributable to enhanced CO_2 is also expected to increase the photosynthetic optimum temperature and the maximum temperature at which each species can grow (warmth, upper right). In addition, tree species should become more tolerant to drought (moisture, upper right). These shifts in response functions, combined with increased photosynthesis in shade (shading, lower right), should enhance biomass per unit area (density, lower right).

Such a realistic simulation of carbon fertilization is not currently possible. Quantitative estimates of the direct CO_2 response functions are unavailable for any major species groups. Indeed, few of the functions have been measured in any tree species. What little is known about CO_2 fertilization effects was simulated to assess the implications of the effects. The

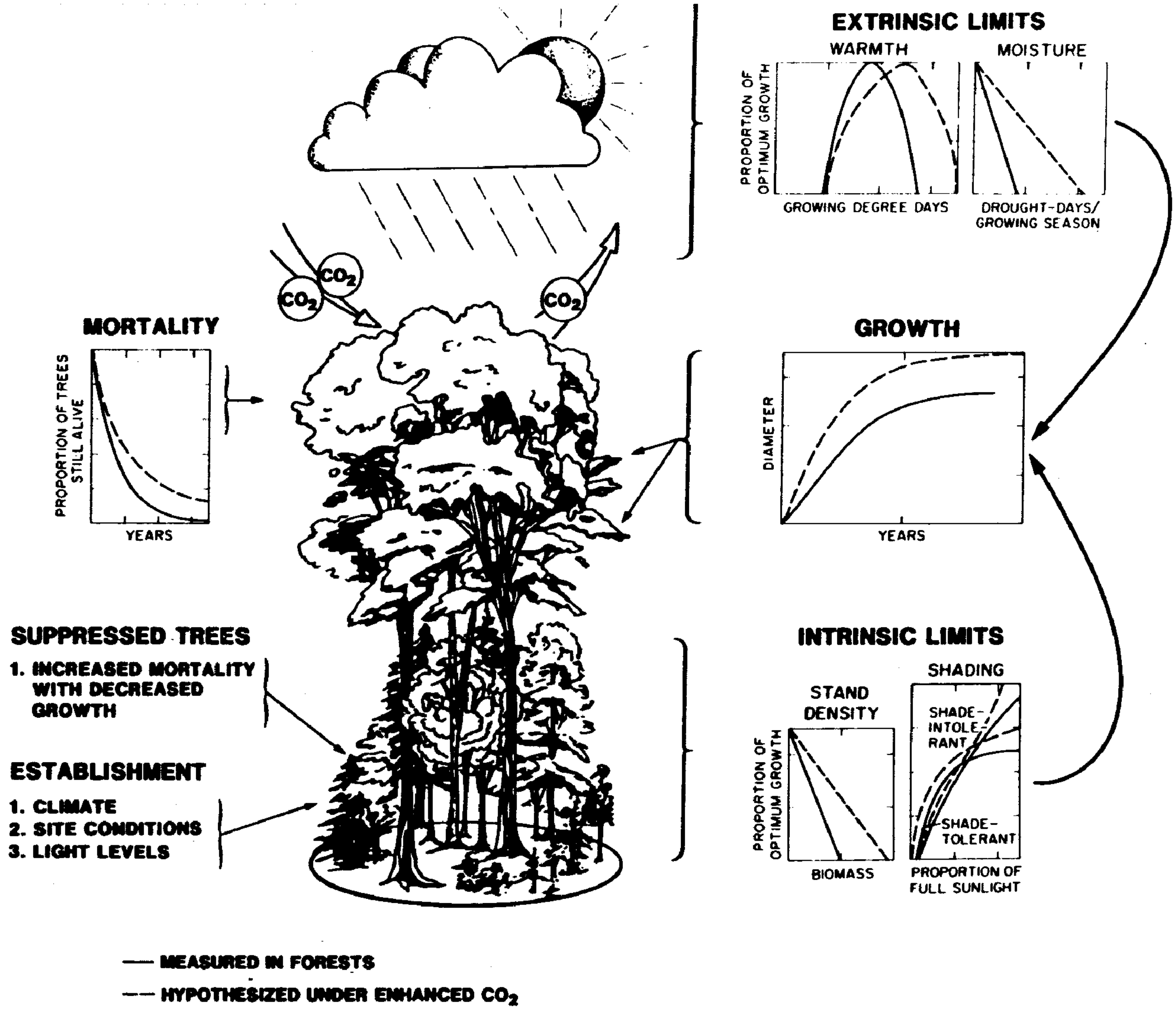

Figure 1. Diagrammatic representation of important processes in forest gap dynamics simulated by the most recent version of the model FORENA (Solomon 1986). Solid curve represents response functions already part of the model. Dashed curves represent possible ways by which response functions could be changed if data were available to characterize the interrelated effects of increased carbon dioxide concentrations on tree growth. Extrinsic stochastic variables and intrinsic deterministic variables control growth (right) differently, depending on tree species and tree age on the plot (center). Trees are removed by mortality as they age or stop growing (left center) and are replaced by stochastic seed sources, sorted by site conditions (left bottom).

model modifications included only the growth function (center right, Figure 1). Note that although only the growth curve is involved, other processes change indirectly. For example, suboptimal temperature and precipitation values become less stressful because of enhanced growth. Maximum ages of each species are unchanged, but the additional growth from CO_2 reduces age-independent (stress-related) mortality, increasing the average age at death for trees of any species.

Simulations contained the assumption that CO_2 effects increase linearly up to a CO_2 doubling, and from doubling to a CO_2 quadrupling. The simulations began with a 400-year period of tree growth from bare plots, followed by a 100-year period during which CO_2 doubled and climate changed to that expected from a doubling of CO_2. During the following 200 years, CO_2 quadrupling occurred in the climate effects [but not in carbon fertilization effects (Sionit et al. 1985)]. A final 300-year period followed, during which climate and CO_2 were stable at the quadrupled CO_2 levels. The parallel climate changes were based on climate model results of Mitchell (1983) and Mitchell and Lupton (1984). Solomon (1986) provides details of model implementation.

The climate and atmospheric CO_2 shifts between doubled and quadrupled CO_2 were simulated to examine forest response under continuously changing climatic conditions. The stable, quadrupled CO_2 climate of the final 300 years was simulated to investigate lags in forest response to the imposition of environmental stability. The reader is cautioned that neither the specific climate values used, nor the presence of specific CO_2 concentrations (i.e., a CO_2 quadrupling), is a condition predicted to occur. The reader is also cautioned to accept the simulation results for what they represent. They are the implications of our current, inadequate knowledge of the processes that will dominate future forest growth in the face of change, rather than being any realistic projection of future forest dynamics.

SIMULATIONS OF FUTURE ENVIRONMENTS

The examination of forest response to concurrent changes in climate and carbon fertilization begins with a simulation of climate change in the absence of fertilization effects. Then the analysis is broadened to include the few carbon fertilization effects measured in greenhouses, and fertilization effects greater than those measured. Forest dynamics were simulated in three places: a boreal forest in west central Ontario, a coniferous-deciduous transition forest in northwest Michigan, and a deciduous forest in east central Tennessee. These were the sites at which Solomon and West (1986) assessed potential reactions to CO_2-induced climate changes by the forest industry. The sites were also among twenty-one at which climate effects of CO_2 increases were simulated (Solomon 1986).

Simulated Response to Climate Changes Induced by CO_2

The initial simulations assume that climate begins to change after year 400 as atmospheric CO_2 increases (Figures 2 through 4), without enhanced growth because of carbon fertilization. During the first 100 years of simulated warming (years 400 to 500), summer and winter temperatures rise respectively 2.5° and 5.0°C at the boreal site, 2.5° and 3.5°C at the transition site, and 3.0° and 2.0°C at the deciduous forest site, based on the climate simulations of Mitchell (1983) and Mitchell and Lupton (1984). At the same

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SIMULATED DYNAMICS AT SITES IN BOREAL, TRANSITION, AND DECIDUOUS FORESTS

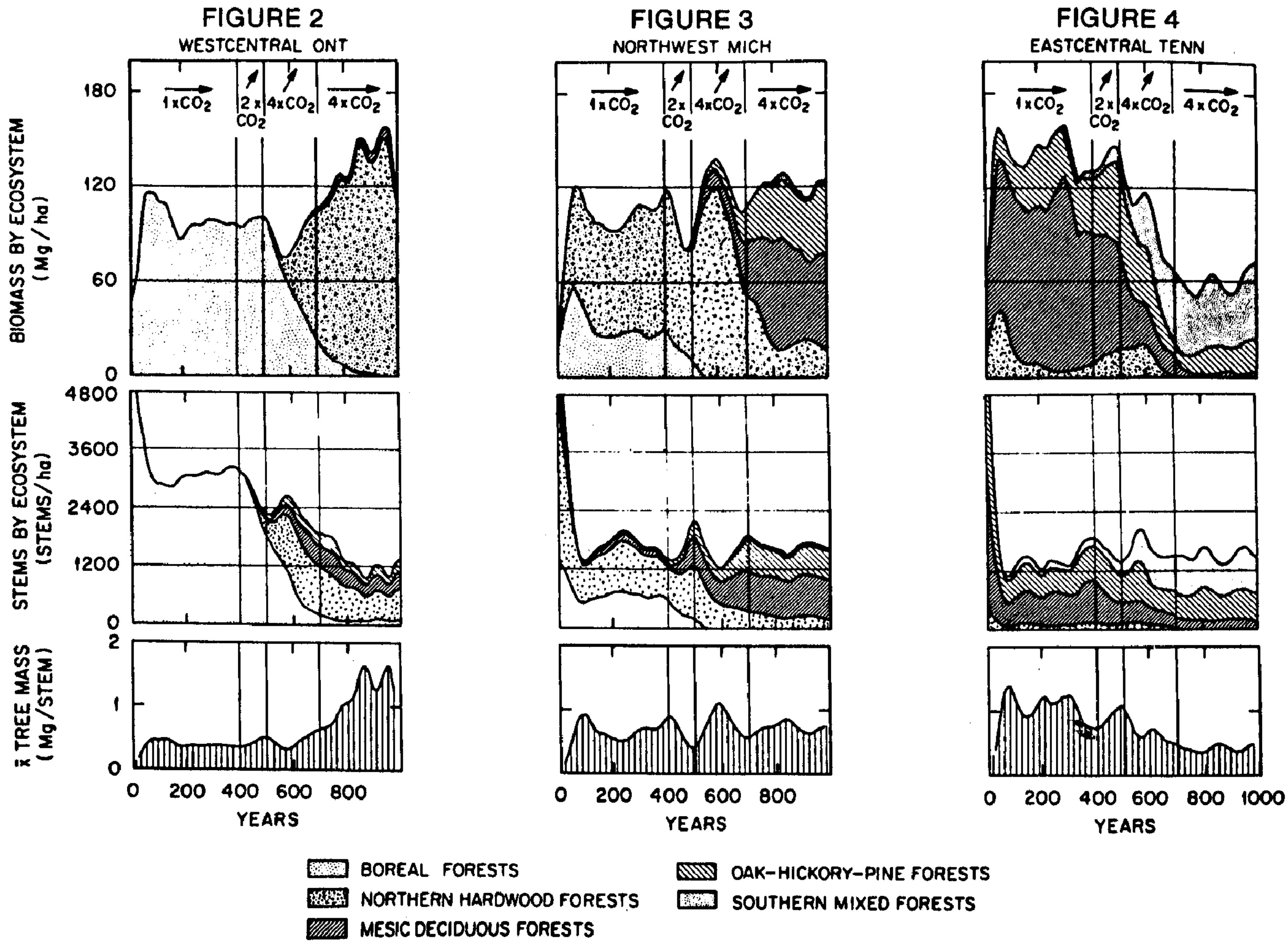

Figure 2. Simulated stand dynamics at the boreal forest site in west central Ontario under four experimental conditions of climate effects. (a) Stand biomass by ecosystem type in megagrams per hectare (Mg/ha). (b) Stems by ecosystem type in stems per hectare. (c) Mass of the average tree in megagrams per stem. Simulation conditions during years 0-400 (1 x CO_2) include modern climate and climate variance; during years 400-500 (2 x CO_2), climate gradually changing to that determined by doubled CO2 at year 500; during years 500-700 (4 x CO_2), climate gradually changing to that determined by quadrupled CO_2 at year 700; and years 700-1000 (4 x CO_2), stable climate and climate variance determined by quadrupled CO_2.

Figure 3. Simulated stand dynamics at the coniferous-deciduous transition forest site in northwest Michigan under four experimental conditions of climate effects. Same as in Figure 2.

Figure 4. Simulated stand dynamics at the deciduous forest site in east central Tennessee under four experimental conditions of climate effects. Same as in Figure 2.

time, annual precipitation is not changed. During the next 200 years of warming (years 500 to 700), summer and winter temperatures rise respectively 2.5° and 4.0°C at the boreal and transition sites, and 2.0° and 3.0°C at the deciduous forest site. Simulated annual precipitation of the 200-year period declines about 25% at the transition and deciduous forest sites, but is unchanged at the boreal forest site.

Simulated stand biomass was unaffected at the boreal location until about year 500, when CO_2 doubling is reached (Figure 2a). In contrast, stem numbers began to decline almost as soon as temperature began to increase (Figure 2b), and average tree size on the stand increased slightly (Figure 2c). In model simulations, as in reality, stress initially led to increased mortality among the youngest (and most plentiful) trees, producing a plot having fewer, primarily mature trees. This shift had little effect on simulated stand biomass. After year 500, biomass declined for 50 to 75 years as warming killed off the large boreal forest species and before new northern hardwoods could grow into the plot. Once the hardwoods began to enhance stand biomass, they continued to increase in biomass and numbers to the end of the simulation, although climate change ended some 300 years earlier.

Stems of deciduous and oak-hickory-pine forest species were relatively common after year 600 (Figure 2b) although they rarely survived to a size large enough to affect stand biomass (Figure 2a). Average tree size (Figure 2c) increased directly with expansion in nonconifer populations (Figure 2a), primarily because the conifers formed forests of smaller stature than did the deciduous trees.

Warming at the transition site (Figure 3) caused an almost immediate response in declining biomass from dieback of mature trees (Figure 3a), in enhanced stem numbers from increased small young stems as the canopy of the simulated forest opened (Figure 3b), and in decline of tree mass (Figure 3c) as large trees died and were temporarily replaced by small, young trees. This immediate response to the warming is logical, considering that almost all species growing in transition communities belong further north (boreal species) or further south (temperate deciduous species). Thus, they were initially under stress, and a change in the climatic status quo enhanced the stress for the dominant northern species. As warming continued during years 500 to 700, biomass (Figure 3a) and tree mass (Figure 3c) first recovered with the growth of northern hardwoods, then declined again as the continued warming stressed the recent northern hardwood immigrants, forcing their demise in favor of more warmth-adapted mesic deciduous and oak-hickory-pine forest types.

Climate changes at the deciduous forest site (Figure 4) generated no discernible shift in any of the forest variables until about year 500, when stand biomass (Figure 4a) and the mass of individual trees (Figure 4c) began to decline. Dieback took the following 200 years. Unlike diebacks at the other two sites, this one resulted in permanent loss of dense forest. The 60 Mt/ha of stand biomass resembles that in open oak woodland and savanna (Olson, Watts, and Allison 1983). One might expect subtropical forests similar to those in Florida today eventually to appear, but the eventual moisture balance excludes subtropical trees. By model year 700, soil moisture values were more similar to those of treeless central Texas today than to those of southern

Florida. Obviously, such a change in biomass could have important implications for the global carbon cycle.

Simulated Responses to Climate and Tree Growth Changes Induced by CO_2

The stand simulations of CO_2-induced climate changes resulted in temporally ordered sequences of forest stand destruction and regrowth. These sequences are likely to differ if carbon fertilization also affects forest growth, particularly because carbon fertilization should postpone mortality. This idea was tested at the three sites where forest response to climate change was simulated.

The model was modified to allow as much as a 20% increase in deciduous tree growth and an 11% increase in coniferous tree growth, with as much as a doubling of CO_2 [from 350 to 650 uL L^{-1} (Sionit et al. 1985)]. Moisture effects on growth were unchanged in coniferous trees (P.J. Kramer, personal communication, 1984) and were decreased by as much as 18% in deciduous trees (Sionit et al. 1985), with as much as a doubling of CO_2. Figures 5 through 7 illustrate stand biomass response in the following ways: to climate change alone (from Figures 2a, 3a, and 4a) and to climate change combined with carbon fertilization effects; as measured by Sionit et al. (1985); at twice those measured (40% increase in deciduous tree growth, 22% increase in coniferous tree growth, 36% decline in deciduous tree water use); and at three times those measured (60% increase in deciduous tree growth, 33% increase in coniferous tree growth, 54% decline in deciduous tree water use).

Continuously increasing carbon fertilization effects decreased the time required after a dieback to repopulate the plot with new trees at the boreal site (Figure 5). Although the dieback began at about the same time, both with and without measured fertilization, recovery began 40 years earlier and was completed about 100 years later in the absence of carbon fertilization. The simulated dieback feature of forest response to climate change was almost absent when the carbon fertilization effect was doubled, and it disappeared entirely under a carbon fertilization effect three times that measured in growth chamber experiments (Figure 5). After climate stabilized at year 700, total stand biomass reached slightly greater values with carbon fertilization than without.

In contrast to results at the boreal site, the simulated forest at the coniferous-deciduous transition site (Figure 6) required only the measured carbon fertilization effect to balance, and thus eliminate, the dieback before a doubling of atmospheric CO_2 occurred at year 500. The deciduous tree communities that eventually controlled the transition forests began to dominate much earlier with than without simulated carbon fertilization. In addition, increasing fertilization increased stand biomass. Indeed, the final rank order of stand biomass at year 1000 was first established less than 50 years after CO_2-induced climate and growth effects began (about year 440 in Figure 6). The sensitivity of these simulated forests to changes in mortality rates was apparently great enough to generate an almost instant response to these subtle environmental changes.

The simulated deciduous forest most clearly responded to the successively greater effects of carbon fertilization (Figure 7). No response was evident before CO_2 doubled. Then, each succeeding increase in CO_2 treatment reduced

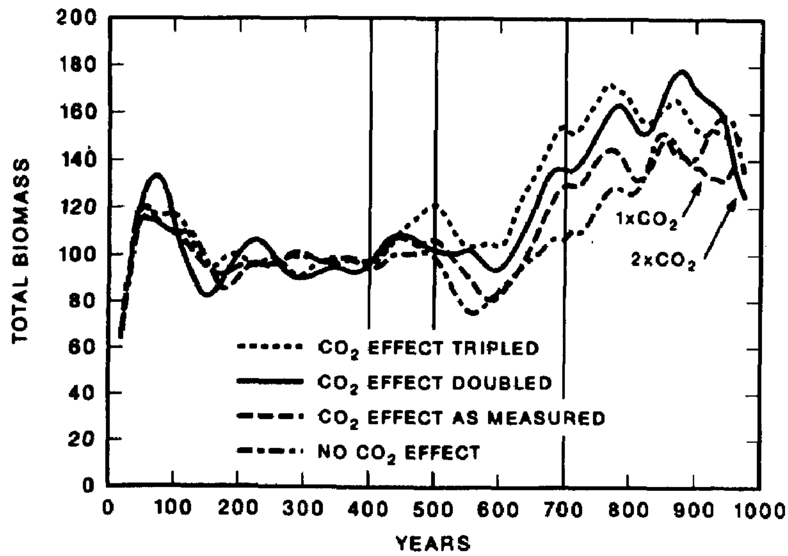

Figure 5. Simulated stand biomass of boreal forest ecosystem in west central Ontario, with varying climatic and CO_2 effects. Climate changes are as in Figures 2 through 4, with successively greater effects of CO_2 on tree species growth. See Figure 2 legend and text for simulation conditions during years 0-400 (1 x CO_2), years 400-500 (2 x CO_2), years 500-700 (4 x CO_2), and years 700-1000 (4 x CO_2).

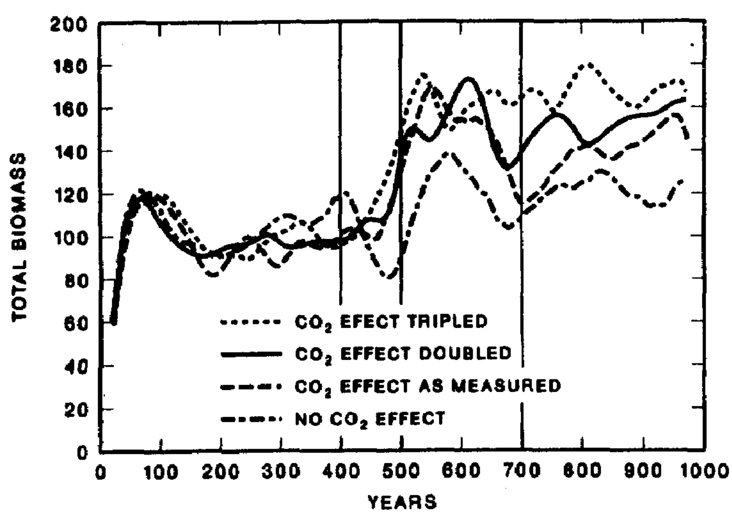

Figure 6. Simulated stand biomass of the coniferous-deciduous transition forest ecosystem in northwestern Michigan, with varying climatic and CO_2 effects. Climate changes are as in Figures 2 through 4, with successively greater effects of CO_2 on tree species growth. See Figure 2 legend and text for simulation conditions during years 0-400 (1 x CO_2), years 400-500 2 x CO_2), years 500-700 (4 x CO_2), and years 700-1000 (4 x CO_2).

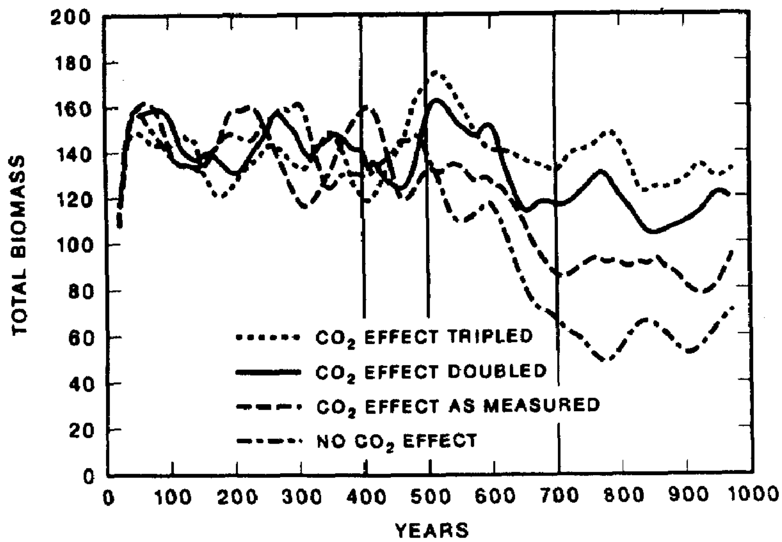

Figure 7. Simulated stand biomass of the deciduous forest ecosystem in east central Tennessee, with varying climatic and CO_2 effects. Climate changes are as in Figures 2 through 4, with successively greater effects of CO_2 on tree species growth. See Figure 2 legend and text for simulation conditions during years 0-400 (1 x CO_2), years 400-500 (2 x CO_2), years 500-700 (4 x CO_2), and years 700-1000 (4 x CO_2).

the effect of climate-induced dieback and further postponed the time at which dieback began. Ultimately, the dieback phenomenon completely disappeared with the application of triple the measured CO_2 effect. As at the transition site, increasing fertilization effects were paralleled by increasing stand biomass, although the final sequence is not apparent until well after the time at which atmospheric CO_2 doubled. Once environmental stability was established after year 700, carbon fertilization effects produced large increases in stand biomass: the measured fertilization effect yielded a 50% increase in biomass (60 to 90 Mt/ha); double the fertilization effect, an additional 28% increase in biomass (90 to 115 Mt/ha); and triple the fertilization effect, an additional 17% increase in biomass (115 to 135 Mt/ha).

DISCUSSION

The foregoing simulations exemplify some of the kinds of forest dynamics that might be expected to occur, based on our current understanding, if increasing atmospheric CO_2 concentrations induce opposing responses by forest trees to direct carbon fertilization and to the concomitant CO_2-induced climate shifts. Overall, forest biomass was affected more in the simulations by the chronic and continuous climate change than by the parallel change induced by carbon fertilization. The exception was the transition forests, in which many tree species grew at the edges of their geographic ranges and thus, were most sensitive to subtle environmental changes.

The dominance of climate changes is logical, considering the scenarios of change. For example, the 2° to 4°C increase in temperature which climatologists expect to accompany a doubling of CO_2 represents the entire current range of mean July temperatures from south to north in the boreal forest of central Canada (Hare and Thomas 1979). In contrast, the parallel fertilization effect of a CO_2 doubling, as measured in long-term CO_2 fumigation experiments, represents only a 20% increase in growth of deciduous trees and an 11% increase in the growth of coniferous trees. If future direct CO_2 effects are to rival or exceed climatic effects, then other, unmodeled CO_2 fertilization features will have to be extremely important.

The simulation results also indicated other forest responses that may occur in the future. For example, significant changes in boreal or deciduous forest biomass may not be detectable during the first few decades of environmental changes that lead to doubled CO_2 and concomitant increased temperatures. However, the oncoming shifts in forest biomass may be presaged by early losses in seedlings and saplings relative to mature trees. Also, early detection of forest responses may be ordered geographically. The sensitivity of simulated transition forests to environmental change implies that coniferous deciduous transition forests and other forests near tree growth limits may be the first to respond to changing CO_2 and climate. This implication is consistent with the suggestion by LaMarche et al. (1984) that they measured CO_2-derived increases in tree growth at high altitude range edges.

These ideas are worthwhile working hypotheses only as long as the forcing and response functions simulated in the model are similar to the forcing and response functions that affect forests in the future. As a tool, the model must accommodate both new and revised knowledge. Accurate simulations are currently restricted by the lack of the specific growth chamber data required to characterize the alternative (dashed) lines in each of the response functions illustrated in Figure 1. In addition, the scenarios of future climate change are also subject to large errors, particularly in the effects of feedbacks among components of the climate system. For example, in the most recent projections of C02-induced climate change by Manabe and Wetherald (1986), temperature increases are twice as great as those used in the simulations discussed here, and soil moisture is 40% less than that used here. The larger climate effects occur because of moisture feedbacks that were not considered in earlier climate model experiments.

The stand simulator could also be greatly improved, even with available data. The model we used (FORENA; Solomon 1986) does not consider certain features that may be important under climate changes, such as the incorporation of localized soil nutrients and turnover, which are available in other models (Pastor and Post 1985). Excluding nutrient cycling from the CO_2-climate simulations should generate greater simulated community productivity than would be the case on present and future landscapes where nutrients limit and will limit tree and forest growth.

Another feature not modeled is the interacting effects of chronic diseases and atmospheric pollutants. Insects, disease, and their vectors (e.g., other insects, fungi, and bacteria) have their own, often complicated, life cycles which depend on weather and climatic events in a manner different from that of the host trees. No model has yet been applied to the complex ramifications of pathogen, insect, and tree-life-cycle interactions under CO_2-induced climate change and other environmental perturbations. A large-scale regional research program is under way at several cooperating institutions to determine the chronic effects of acidic precipitation on forests, based on field studies and the forest-stand model (for example, see McLaughlin et al.

1983). This effort might be extended to include insects, pathogens, and other air pollutants, as well as climate change.

Finally, the model is inherently limited by the presence of mountains, oceans, and other nonclimatic restrictions upon the geographic ranges of tree species. Within the present form of the model, such boundaries must be assumed to coincide with climatic barriers, although this is clearly not the case for some species.

The present model experiments on effects of carbon fertilization indicate that the primary impacts could involve accelerated growth, increased aging, and reduced impacts of the climate-related environmental changes simulated without CO_2 fertilization. Even with unrealistically high growth enhancement, hypothetical tree growth and forest community productivity did not exceed current known values for those communities. More data from many species on the responses of mature (as well as seedling) trees to increased atmospheric CO_2 concentrations are required to characterize potential CO_2 fertilization and increased water-use efficiency. Indeed, there is a critical need for evidence that any tree life stage besides seedlings will benefit from CO_2 fertilization. At present, we can expect such benefits only in plants growing in noncompetitive, nonlimiting agricultural systems. Thus, data on the presence and effects of CO_2 fertilization and water-use efficiency phenomena must be obtained from trees growing in unmanaged stands, in order to hypothesize and then to reliably simulate the effects of carbon fertilization on forests.

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Historical Changes in Forest Response to Climatic Variations and Other Factors Deduced From Tree Rings

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INTRODUCTION

Hecht (1985) defines "climate" as a time-transgressive phenomenon being the average state of the atmosphere over periods of 25 to 30 years or more. While we have considerable knowledge of the broad characteristics of climate, there is much less knowledge of the major processes of climatic change (National Academy of Sciences 1975). Proxy data, i.e., substitutes for climatic information, can span time periods before instrumental climatic records were kept and thus are an important source of information on the long-term history of climatic variations (Hecht 1985). Tree rings provide a unique proxy record of seasonal to century-long climatic variations for several reasons. First, usable trees can be found in all temperate lands and many trees are available for replication. Furthermore, the information obtained from these trees can be dendrochronologically dated and arranged in an accurate time sequence. Finally, the ring features can be measured easily and combined for many trees to obtain a well-behaved time series, which is particularly relevant to forest response as ring width is a growth measurement.

DENDROCHRONOLOGY AND DENDROCLIMATOLOGY PROCEDURES AND PRACTICES

It is well known that yearly tree-ring width sequences, called chronologies, have been used to date structures, such as archaeological ruins, historic buildings, and early Dutch paintings (Anonymous 1977; Baillie 1982; Trefil 1985). A.E. Douglass, an astronomer working in Arizona, is credited with developing tree-ring dating (1919, 1928, 1936) and is considered the founder of the discipline of "dendrochronology" (Webb 1983). "Dendro" is the root word meaning tree and "chronology" means "time." The discipline is most easily understood as the systematic use of tree-ring crossdating to study problems involving time and factors of the environment. Crossdating was first used to date beams or charcoal fragments from archaeological and historical structures in the North American southwest, and the technique provided archaeologists with the most precise time control ever devised (Douglass 1935, 1937).

Crossdating uses the year-to-year synchrony of ring features associated with past fluctuations in climate to place each ring in its correct time sequence. Various discrepancies in ring synchrony suggest where ring counts may be in error. The source of each error is deduced from the ring structure using knowledge of tree growth, and the dating is adjusted. This tedious procedure continues until all apparent discrepancies are identified and corrected for every ring in every tree collected from the site. If this is done carefully, all rings will be assigned to the correct year in which they were actually produced and the data can be combined to obtain an average yearly response of the trees to variations in climate.

The science that uses dated tree-ring sequences to reconstruct past climate (Douglass 1914; Schulman 1947, 1951, 1956; Fritts, 1976; Hughes et al. 1982) is referred to as dendroclimatology. It is not as well known that these same dated tree-ring sequences can be used to study various ecological problems; in these cases the term dendroecology is used.

A variety of structural characteristics of tree-rings, such as width, wood density (Schweingruber, Braker, and Schar 1978b), and vessel size (Eckstein and Frisse 1982), show variability from one ring to the next. The variations in ring width have been studied most often (Fritts 1976; Baillie 1982) because width can be observed and measured easily from a finely sanded surface by using a hand lens or dissecting scope.

The wood can be X-rayed (Polge 1963, 1966, 1970), and the image on the exposed film can be scanned to obtain detailed ring density measurements. These, in turn, can be correlated with climatic variations as well as various physical, chemical, and biological features of the environment (Keller 1968; Parker and Henoch 1971; Fritts 1976; Huber 1976; Schweingruber, Braker, and Schar 1978a, 1978b; Conkey, 1982a, 1982b).

The effects of nonclimatic variations on ring-width growth are minimized by coring only trees with characteristics that indicate climate was highly limiting to growth. Additional random variability caused by site differences is controlled by sampling and averaging the effects of many trees from a narrowly defined target site (Fritts et al. 1965; Fritts 1969; LaMarche 1974a; LaMarche 1982; Norton 1979, 1983). A narrowly defined target site helps to minimize the differences between tree microsites which could obscure that portion of the response because of variations in macroclimate. In American work, from ten to forty or more of the oldest trees with the necessary characteristics are cored and two cores are usually obtained from each tree in the site.

The samples are prepared and crossdated before performing the desired analysis. When crossdating is complete, the dating is checked by the computer (Holmes 1983) or by another person, the rings are measured, and the measurements are standardized. Standardization identifies the slowly varying growth changes in individual trees associated with increasing age and local conditions of the site (Figure 1a). These changes are estimated, in this case, by fitting a curve or straight line to each dated and measured series. The width is divided by the estimate to obtain an index which is stationary

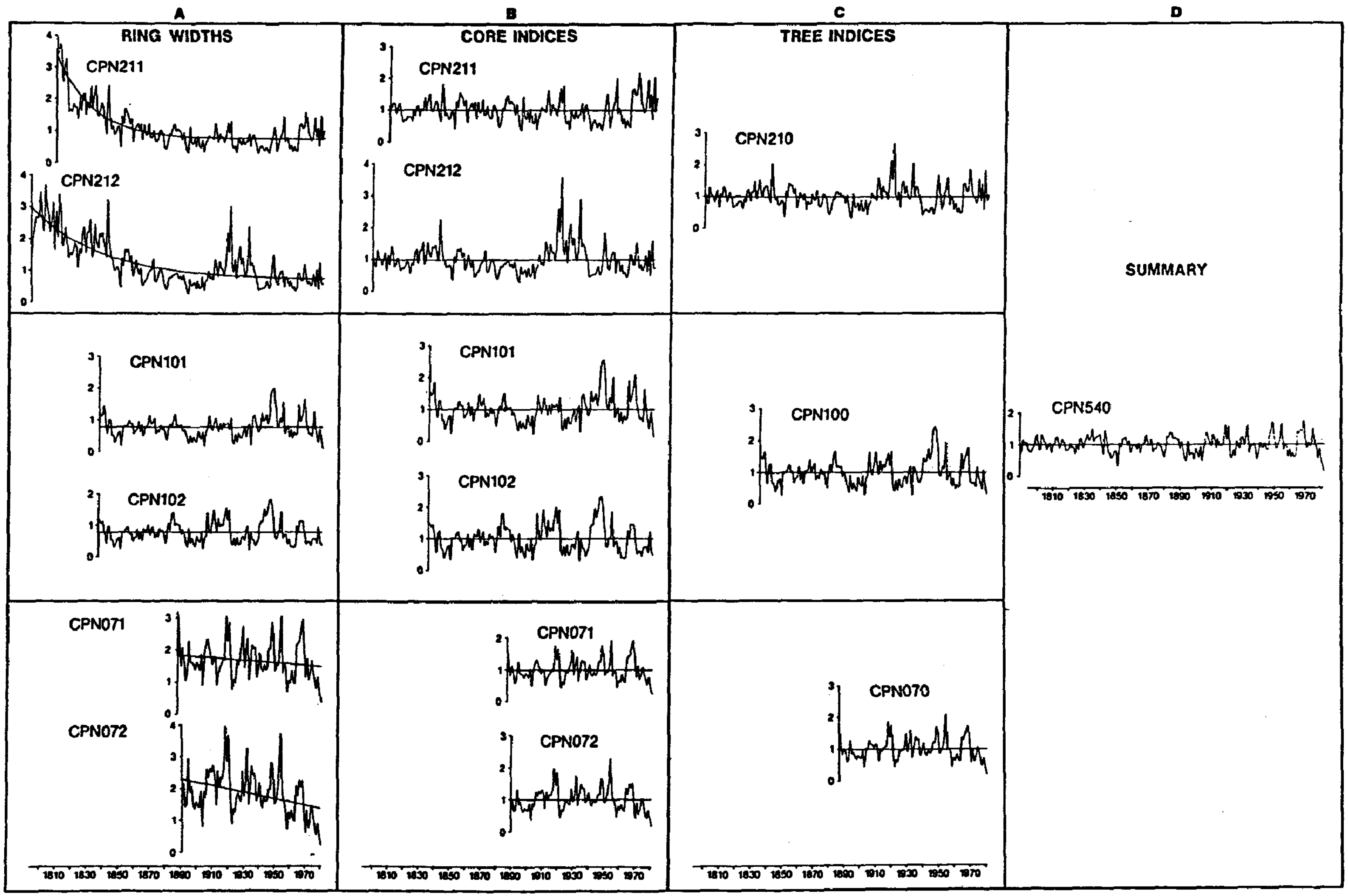

Figure 1. The dated ring widths are transformed into a standardized chronology by: (a) fitting a curve or straight line to the ring widths from each core, (b) dividing by the values of the fitted curve to obtain the indices, (c) averaging the cores for each tree to obtain the indices, (d) averaging the cores for each tree to obtain the tree indices, and (e) averaging the tree indices to obtain the chronology for the site.

over time (Figure 1b). These indices can then be averaged for the cores within each tree (Figure 1c). These in turn are averaged for all trees to obtain a mean chronology for a species and site (Figure 1d). This standardized chronology reflects the relative variations in ring-width growth associated with cliamte. However, standardization must be applied carefully because in certain circumstances it cannot distinguish between standwide nonclimatic factors and those due to climate, and a linear or downward trend in climate might be indistinguishable from age-related variations in growth.

LONG TREE-RING CHRONOLOGIES APPLIED TO ENVIRONMENTAL QUESTIONS

The growth of trees from many high-altitude or high-latitude sites are most often limited by low temperatures, and many of these trees may attain great age. Ring-width chronologies from these trees largely reflect temperature variations (LaMarche 1974a, 1974b, 1978; LaMarche and Stockton 1974; Schweingruber et al. 1978; Schweingruber, Braker, and Schar 1978, 1979; Cropper and Fritts 1984), although other factors such as snow depth can be important (Graumlich and Brubaker 1986). Such chronologies have been plotted and used directly as proxy records of temperature variations and change (Figure 2). However, LaMarche et al. (1984) found a growth increase in high-altitude trees from the Great Basin, U.S., beyond the effects they expected from temperature trends. They hypothesized that this could be a carbon dioxide fertilization effect. Graybill (1985) is developing a more extensive network of high altitude site chronologies that ranges from the Rocky Mountains to the eastern edge of the Sierra Nevadas for use in further testing of this hypothesis. In preliminary analyses that used upper treeline (3400 m) data from six sites in the Great Basin (P. longaeva) and three from Colorado (P. aristata), the chronology scores on the first and only significant principal component for each area demonstrated a similar rise (Figure 2) to those reported by LaMarche et al. (1984) and Graybill (1986a). In contrast, the component scores of four other Great Basin chronologies (P. longaeva) from relatively high altitudes (2600-2900 m), yet near the lower altitudinal limits of growth for the species, demonstrated different growth trends (Figure 2). Further investigation is required to understand the more precise relationships of tree growth in all of these high-altitude sites to temperature, precipitation, carbon dioxide, and other critical factors.

The rings of conifers from their lower altitudinal limits (Figure 2) in semiarid western North America are likely to reflect drought resulting from deficits of soil moisture and evaporative stress caused by high temperatures, wind, and intense solar radiation at the tree sites (Fritts 1976; Stockton and Meko 1983). The interactions between different climatic factors make these chronologies difficult to interpret, although generally the ring width variations can be regarded as a more or less direct response to soil moisture due to precipitation variations with an inverse response to temperature.

CALIBRATION AND VERIFICATION

Regression and related multivariate techniques can be used to relate many climatic factors to an indexed chronology or to convert the indexed chronologies into estimates of one or more climatic factors. The tree-ring data are calibrated with instrumental climatic measurements, and the degree of fit is expressed as percent calibrated variance.

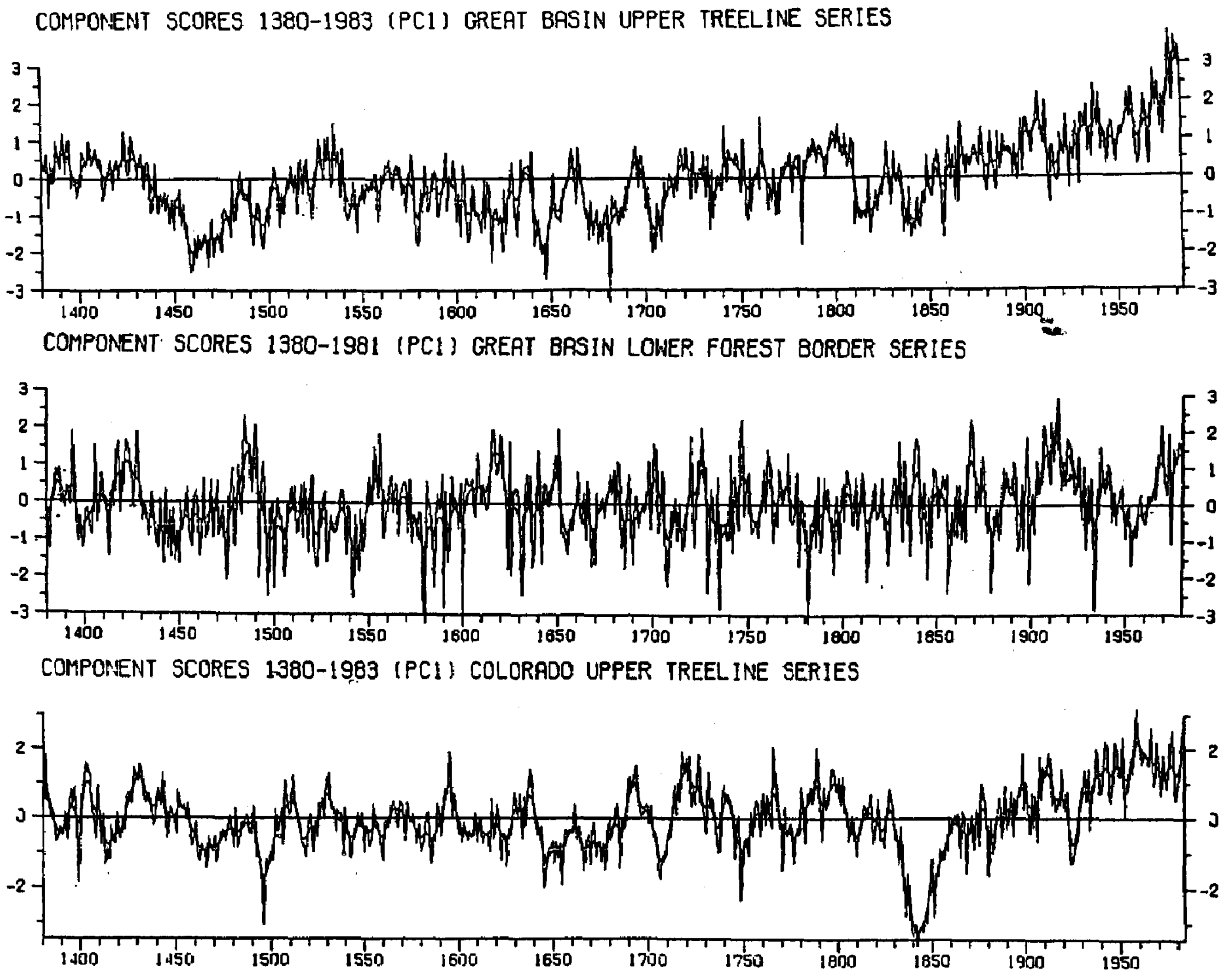

Figure 2. The first principal component scores from 1380 to 1983 for (a) Great Basin upper treeline series, (b) Great Basin lower forest border series, and (c) Colorado upper treeline series (Graybill 1986).

The first type of calibration is called a "response function" because the coefficients can be interpreted as the response to climate. Cooper, Blasing, and Fritts (1974) used response functions in a CIAP study to estimate the effect of a 2°-3°C temperature decrease and a 5% change in precipitation on ring-width growth throughout arid sites in the west. A type of response function can be used to separate the effects of climate on growth from those due to pollution or other possible agents of forest decline (Cook in press).

The second type of calibration is called a "transfer function." Several chronologies at different lags may be used as predictors of a climate-related variable at one or more sites. Least squares techniques are used to obtain the "best-fitting" relationships over the calibration period (Lofgren and Hunt 1982). A transfer function is obtained with coefficients that convert tree-ring chronology information into estimates of the calibrated variable of climate. The reliability of the coefficients of the equation and its estimates can be tested by withholding some of the observations to test whether the reconstructions for those particular years are correct. This procedure is called "verification." If the verification tests are significantly better than expected by chance, the reconstructions are considered a verified result (Gordon 1982).

After they are verified, the verification and calibration statistics may be compared for different models to help select which reconstructions are best. For example, Cook and Jacoby (1977) calibrated tree-ring chronologies with drought indices in the Hudson Valley, New York, verified the reconstructions with independent data, and then used the best verfied model to reconstruct past drought. They also used tree rings to reconstruct streamflow for the Potomac River (Cood and Jacoby 1983). Stockton and Jacoby (1976) used a grid of chronologies within the Colorado River Basin to reconstruct Upper Colorado long-term streamflow trends. Some other dendroclimatic reconstruction studies include Briffa et al (1983), Conkey (1982b),. Duvick and Blasing (1981), Fritts, Lofgren,and Gordon (1979), Garfinkel and Brubaker (1980), LaMarche and Pittock (1982), Rose, Dean, and Robinson et al (1981), Stockton and Meko (1983) and Graybill (1986b).

A large grid of tree-ring chronologies can be calibrated with large-scale variations in climate over a geographic grid (Fritts et al. 1971; Fritts, Lofgren, and Gordon 1979; Stockton and Meko 1975, 1983; Lough and Fritts 1985). These studies used canonical regression of principal components of tree-ring chronologies on principal components of climate, drought, or seasonal averages of the Southern Oscillation index.

SPATIAL ANALYSIS

A total of 65 arid-site chronologies were selected (Fritts and Shatz 1975) that spanned the period from 1600 to 1963 with a geographical coverage extending from the North Pacific coastal states to the Black Hills of North Dakota and from the Canadian Rockies to Durango, Mexico. Three sets of climatic data were selected for calibration with the tree-ring chronologies. The first two were arrays of seventy-seven data points for surface temperature and ninety-six data points for precipitation in the U.S. and southwestern Canada. The third set was an array of seasonal sea-level pressure at ninety-six grid points from 100°E to 80°W and 20°N to 70°N. All data for the years 1901 and 1961 were complete.

A large number of statistical models of different structure were calibrated (Fritts and Lough 1985) and verified (Gordon 1982). Stepwise canonical regression, modified from Blasing (1978) (also see Fritts, Lofgren, and Gordon 1979; Lofgren and Hunt 1982), was used to calibrate principal components of growth with principal components of climate. This stepwise analysis reduced the large number of predictor principal components (fifteen or thirty) to one to seven canonical variates. A transfer function was obtained and applied to the tree-ring principal components to reconstruct seasonal temperatures and precipitation at each station and sea-level pressure at each grid point from 1602 to 1962.

The estimates from the two or three models with the best calibration and verification statistics were averaged for each variable and season, and the average of the seasonal models was averaged further to obtain annual estimates. The calibration and verification statistics were recalculated using the seasonal data and the annual instrumental values. Each level of combination showed improvements in statistics above those expected by chance [See Fritts and Lough (1985) for more discussion of the model treatments].

It was concluded from these results that the large-scale regional patterns of climatic variation were calibrated much better than variation at the individual grid points or stations (Fritts and Lough 1985). One could take advantage of this higher reliability of the large-scale patterns by examining regionally averaged reconstructions or by averaging results for several seasons or years. In the following examples, the individual reconstructions have been combined and averaged over space or time to take advantage of the greater reliability of the combinations.

The reconstructions for the decade 1831-1840 are used in Figure 3 to illustrate the spatial reconstructions that were obtained from analysis of spatial growth patterns. The left-hand portion of Figure 3 is a map of average tree growth for 1831-1840 expressed as departures from the long-term average values. The upper middle and upper right-hand maps are the reconstructed average temperatures for winter and spring. Those below are the reconstructed total precipitation for winter and spring. Above average growth over most of the map is transferred into cool or cold winter temperatures especially in the northern high plains with spring temperatures slightly above average for the northwest and southeast. Moisture is reconstructed as much as 60% above average for winter and spring for large areas of the map.

The average annual temperature, precipitation, and sea-level pressure were mapped by decade from 1801 to 1850 (Figure 4). The east-west differences in temperature and the general wetness of the 1831-1840 decade is evident. This was actually the wettest decade that was reconstructed, and according to Edward Cook (personal communication) the tree-ring data from the eastern U.S. indicate that the wetness did indeed extend eastward. The pressure anomalies that were reconstructed suggest a southward displacement of storms in the North Pacific and enhanced storm activity from the North American southwest to eastern Canada.

The maps in Figure 4 for other decades indicate that the 1800s and 1810s were generally warm, with drought in much of the west and wetter conditions in the east, although the verification statistics for the Atlantic and Gulf coast indicated the reconstructions were unreliable that far east and south of the

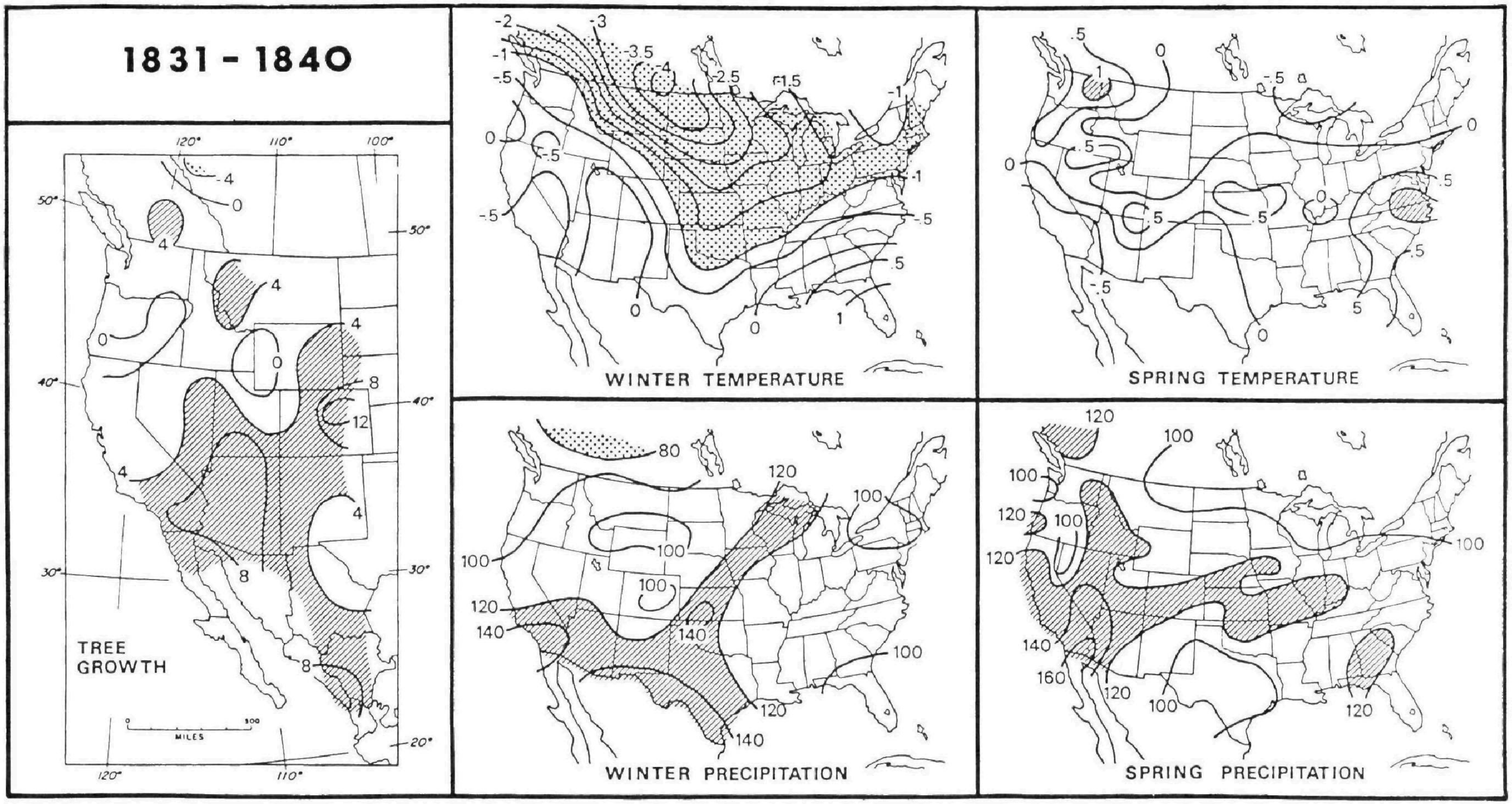

Figure 3. Mean anomalies in tree-ring width indices and reconstructed temperatures and precipitation for winter and spring of 1831-1840. Tree-ring data are normalized values multiplied by 10, calculated using the 1601-1963 means and standard deviations. The climatic data are departures expressed as °C or % of the 1901-1970 mean values.

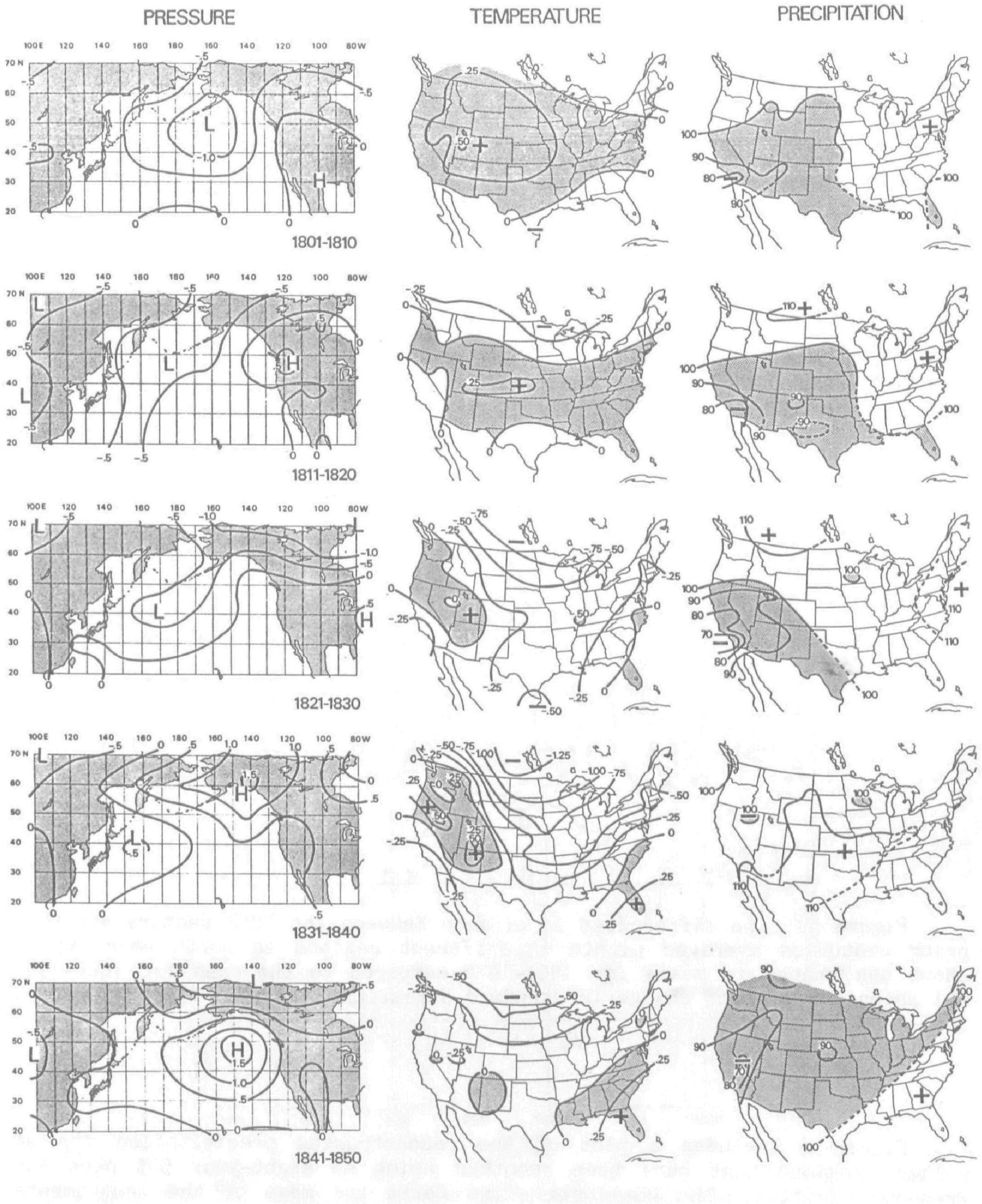

Figure 4. The mean reconstruction sea-level pressure (MB), temperature (°C), and annual precipitation (%) for decades in the first half of the 19th century plotted as departures or percentages of the 1901-1970 mean values. Shaded areas are warm and dry anomalies.

tree-ring grid. There was cooling in the 1820s and drought in the southwestern deserts. Temperatures were closer to the 20th century average in the 1840s, and below average precipitation was reconstructed for most of the country.

The reconstructions were averaged for eleven regions over the contiguous U.S. and southwestern Canada; the averages and standard deviations of the annual data before 1901 were calculated and the differences between these figures and the 20th century data were calculated (Figure 5) to examine the question of how typical the 20th century statistics are compared to those from the prior three centuries. The temperatures from 1901 to 1970 have risen 0.20° to 0.93°C for regions 5, 7, 8, 9, 10, and 11, but the temperatures in the remaining five western regions have fallen in the other regions. The data to the extreme right of Figure 5 indicate that in the western states the standard deviations of both temperature and precipitation as reconstructed were to have declined in the 20th century.

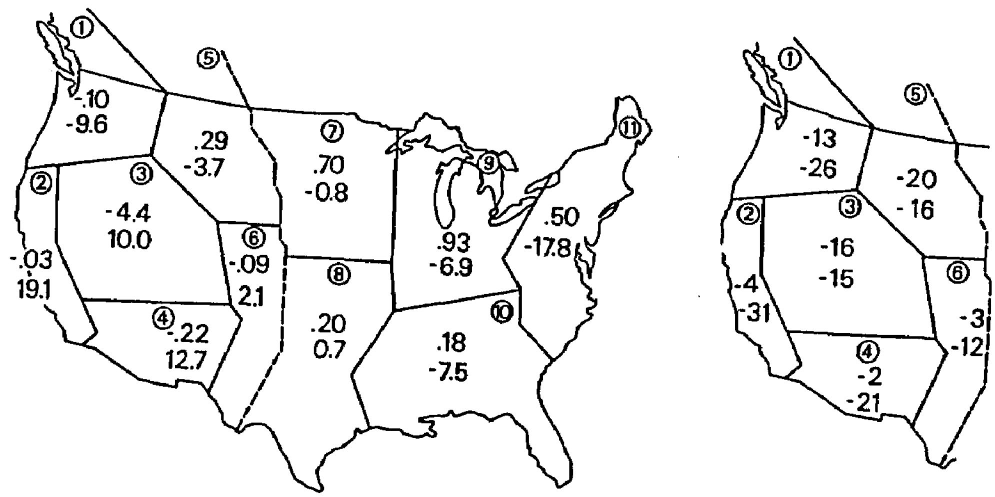

Figure 5. The differences in climate between the 20th century and three prior centuries averaged within 11 different regions in North America; (a) shows the change in means for 1901-1970 compared to the mean for 1602-1900; (b) shows the percent change in standard deviations for 1901-1961 compared to 1602-1900.

Figure 6 includes a plot of the reconstructed precipitation for six western regions that have been smoothed using an eight-year 50% pass low-frequency filter. The horizontal line marks the mean of the instrumental record for 1901 to 1970. The dots on the right show the smoothed averaged instrumental data with which the tree-ring chronologies were calibrated. The amount of similarity of the two data sets for 1901 to 1962 is proportional to the variance calibrated. (The 1901 to 1905 and 1959 to 1963 periods include end effects of the filter.)

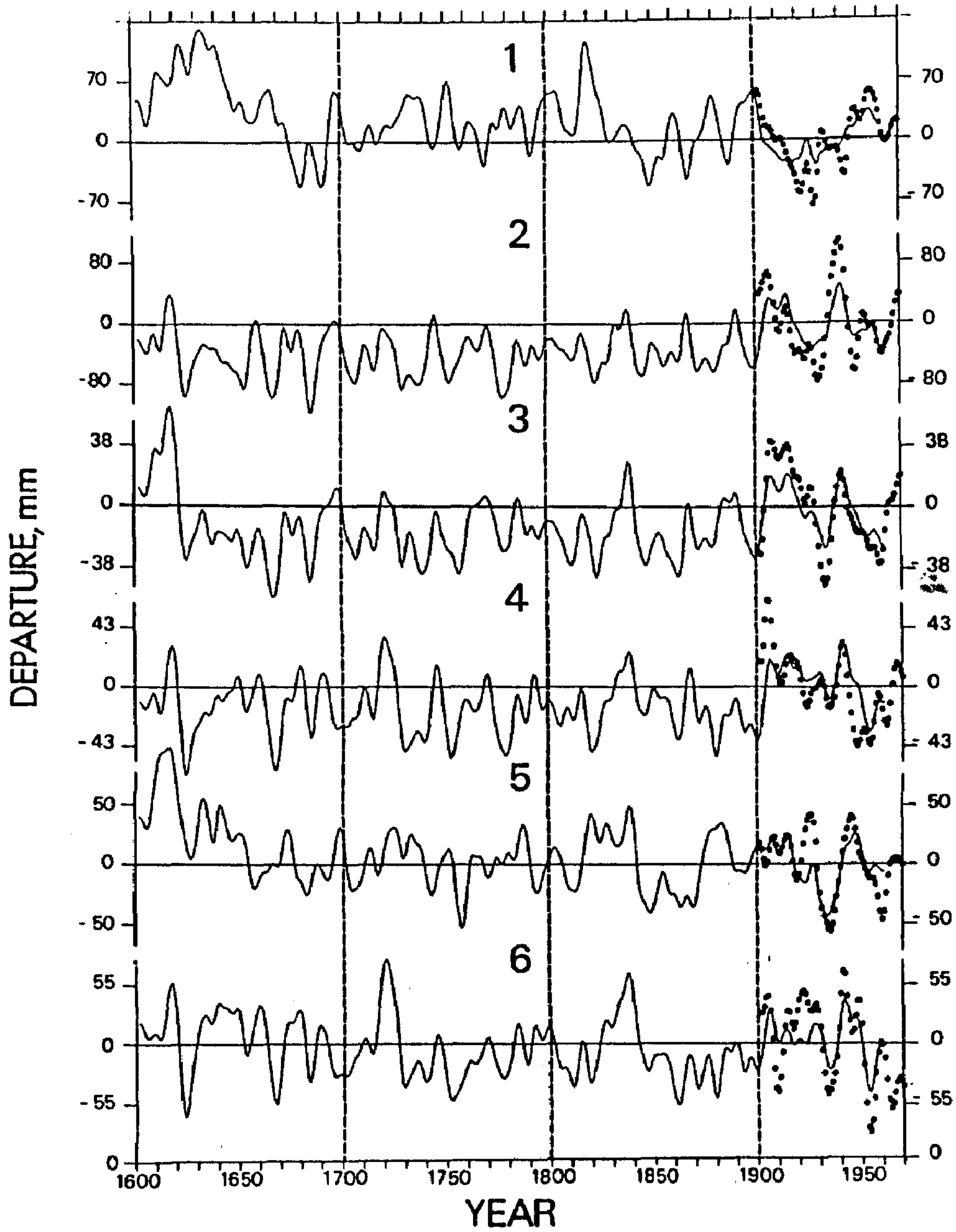

Figure 6. The regionalized annual precipitation reconstructions for six western regions treated with a low-pass digital filter with a frequency response of 50% at periods of eight years and plotted as departures from the 1901-1970 averages. Dots on the right are the filtered, regionalized instrumental data used for calibration.

Region 3 is made up of eleven climatic stations, including the area of the Great Salt Lake with which the smoothed reconstructions and climatic data were highly correlated. These reconstructions provide an enlarged data set to evaluate the present high level of the Great Salt Lake, which exceeds all previous measurements. It appears from this time series that precipitation in this region has been below the 20th century mean since 1625. It was reconstructed to have been especially high in the early 1600s, and therefore, it is possible that the current high levels could become higher. However, this extreme climatic condition was uncommon over the last 300 years, and therefore a rise in lake level, while possible, is not the most probable outcome to expect.

The reconstructions allow spatial analysis of climatic variations for time periods when the coverage of instrumental data was inadequate. For example, large explosive volcanic eruptions can inject enough ash and gas into the upper atmosphere to alter the global energy balance and consequently decrease the average surface air temperatures of the Northern Hemisphere (Taylor, Gal-Chen, and Schneider 1980; Self, Rampino, and Barbera 1981). Past empirical studies of the effects of volcanic eruptions on surface climate have been limited by the relatively small number of major eruptions occurring after the beginning of the 20th century and the poor coverage of the instrumental data prior to the 20th century.

Lough and Fritts (Submitted) used the reconstructed temperature data to test whether there was a significant spatial response following volcanic eruptions. The years of major eruption, called key dates, were selected from the historical volcanic eruption chronologies published by Lamb (1970), Hirschboeck (1979/80) and Newhall and Self (1982). There were twenty-six volcanic events occurring in 24 years within the period 1602 to 1900 that were suitable for the analysis.

The average temperatures for the years associated with the selected key dates were calculated for the five years before and for zero to two years after the eruptions. The difference (the average for the years after the eruptions subtracted from the average for the years before the eruptions) was then calculated for each station and mapped, and the 95% confidence level was calculated using Student's t-test.

The volcanic events were first divided into three groups according to the latitude of the eruptions to test whether this influenced the subsequent climatic impact. These data suggested that a large part of the U.S. appears to cool following low-latitude volcanic eruptions, but significant warming in the far western states is evident.

The seasonal reconstructions of temperature were then examined using key dates from the low-latitude data set (Figure 7). These data indicate that the warming reconstructed in the west is most extensive in winter with 36% of stations showing significant differences. Significant cooling is reconstructed in spring for the central states (38% of the reconstructed points are significant). In summer, a cooling is reconstructed east of the Rocky Mountains while a warming is reconstructed in the far west, including Nevada and the northern Rocky Mountains of the U.S. (61% of the differences are significant). The largest differences are centered over the Mississippi River drainage.

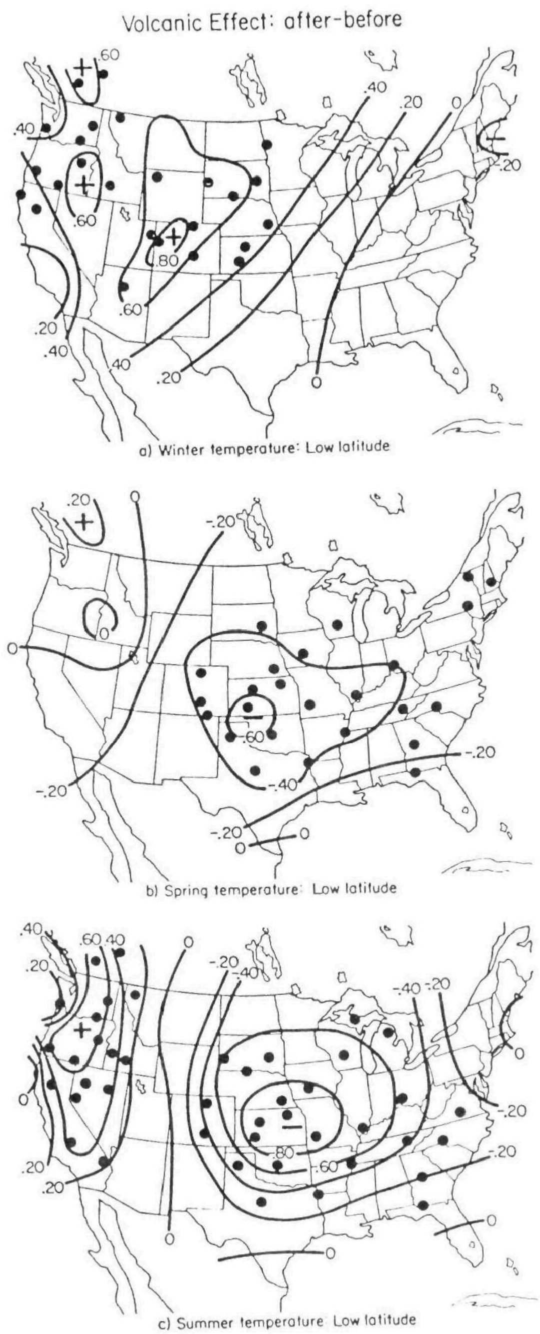

Figure 7. Average reconstructed temperature differences (°C) between the average of years 0 to 2 after key dates minus the average of years 1 to 5 prior to key dates for low-latitude eruptions for (a) winter, (b) spring and (c) summer. (Heavy dots denote stations at which the temperature difference is significant at the 95% confidence level.)
Source: Lough and Fritts, in press.

The reconstructions of temperature variations over North America were used to determine that there are significant responses in the temperature patterns forced by large volcanic eruptions and that low-latitude volcanic activity seems to have the most obvious effect. Seasonal variations in the major centers of temperature change caused by volcanic activity also are apparent.

CONCLUSIONS

The following conclusions can be made with regard to historical changes in forest response to climate variations and other factors deduced from tree rings:

- There are many types of proxy records of past climate. Tree rings are unique in that they can be obtained from most temperate and subpolar forests, and they can provide information on seasonal- to century-long variations in climate.

- The rings from old, climate-stressed trees are particularly valuable for reconstructing climate over time periods before the instrumental record began or when the instrumental measurements were incomplete.

- The rings must be dendrochronologically dated to assure the correct time control, and usually standardization must be applied to the measurements to obtain a mean chronology, which is a well-behaved time series with a strong signal of climate.

- These chronologies can be interpreted directly if one climatic factor, such as temperature, is both limiting and linearly related to the chronology index. An interesting exception is shown, where increasing ring width of high-altitude trees from the Great Basin looks more like the rising levels of carbon dioxide than the global warming effect. More work is needed to establish the exact cause of increased growth in this case.

- Calibrations of chronology value with climate predictors produce a response function that can be used to estimate the effect of a specific climatic change on tree growth or to remove from a chronology that variance related to climate to assess forest decline effects.

- Calibrations of climate variations with tree-ring chronology predictors produce a transfer function. Independent climatic data are usually reserved to allow for verification of the transfer function result.

- Many applications use several tree-ring chronology predictors and reconstruct one climate series at one time. More complex models include many predictands and predictors. A study to reconstruct maps of temperature, precipitation, and sea-level pressure from arid-site tree-ring chronologies provides a data source for past climatic variations and change.

- The reconstructions of temperatures were used to examine whether there is any significant spatial response of North American temperatures to large volcanic eruptions. A large part of the eastern and central United States was found to cool in response to volcanic eruptions, but significant warming occurred in the western states. The extent of this warming is greatest in the winter and least in the summer. This result, although based on indirect dendroclimatic evidence, is important because it suggests that previous conclusions, which identified large-scale average temperature decreases, should be modified to include regional-scale warming at least in the western United States.

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How Changed Weather Might Change American Agriculture

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ABSTRACT

Primary production of food for man and animals from solar energy is in crops, which grow outdoors exposed to the weather. Because crops make food from CO_2, more CO_2 benefits them. If weather changes with changing CO_2, the benefit of CO_2 may be tempered.

For specified changes in weather, yields can be calculated from plant physiology or records of past weather and yield; for specified changes in weather and CO_2, yields can be calculated from plant physiology. Changes in weather may cause disproportionate or nonlinear responses as when plants freeze or a pest intervenes, making probabilities rather than averages relevant. A small absolute change in probability may be a large relative change in probability and an even larger ratio of relative change in probability to relative change in weather.

Because irrigation uses the difference between rain and evaporation, the change in the supply of irrigation water will logically be relatively greater than the change in rain, especially if the drier weather is warmer. Only anecdotal history may prepare us for the ramifications of changes in weather. Adaptations like migration, commerce, and new varieties, species, or husbandry may temper the impact of changed, especially gradually changed, weather.

In this paper, I have drawn upon my chapter in Changing Climate, NAS Press (Waggoner 1983), especially calculations of Clarence Sakamoto described therein, and upon my unpublished manuscript prepared for "Genetic Agraria y Sociedad," a conference sponsored by Fundacion Valencian de Estudios Avanzados y el Capitulo Espanol del Club de Roma. The long word precipitation is replaced by the short word rain, which here means all forms of precipitation.

INTRODUCTION

Although agriculture encompasses animal husbandry and aquaculture, the growing of crops holds the honor of first place, performing the primary production or transformation of solar energy to food energy for ourselves and other animals. Hence, if the primary production of crops fails, all fails. Crops have a further importance because they are peculiarly susceptible to the projected changes in CO_2 and weather. CO_2 is the raw material of photosynthesis, which transforms solar energy to food energy. Crops generally stand unprotected in the weather, and even crops seemingly protected from drought by irrigation ultimately are affected by rain and evaporation. Thus, although the projections of meteorologists are uncertain, agriculturalists reasonably ask: "How will crop production be changed by a warming of 1°C and a 10% decrease in rain and what can agricultural scientists do?"

American crop production is important because it feeds us. It is also important to the world because, for example, it produces approximately 70% of the world's annual 500 million ton wheat crop and 25% of the world's 400 million ton corn crop.

RISING CO_2 SPEEDS PHOTOSYNTHESIS

The direct effect of CO_2 concentration is upon photosynthesis, which will be speeded by increasing CO_2 above 340 ppm. When crops are grown experimentally with increased CO_2 concentrations, yields increase approximately 1/8% per ppm CO_2. Although one might expect other factors to limit the benefit of CO_2, it increases growth whether water or nitrogen is deficient (Waggoner 1983).

At 340 ppm, net photosynthesis is somewhat faster in "C4 plants" like maize, than in "C3 plants" like wheat. Maize photosynthesis, however, is saturated by only 450 ppm CO_2, whereas that of wheat increases to fully 850 ppm. Thus, the increase in photosynthesis per increase in CO_2 is somewhat greater for C3 plants than for C4 plants. Because more CO_2 would logically speed the photosynthesis of the less productive C3 more than that of the more productive C4, the gap between them would lessen or even be reversed by rising CO_2. Such turnabouts as more aggressive C3 weeds in fields of C4 maize have been suggested (Waggoner 1983).

In dry weather, increased CO_2 has another benefit. Increased CO_2 narrows stomata, which decreases transpiration in crops in the field (Waggoner et al. 1964). Baker (1965) found that doubling CO_2 from 300 to 600 ppm decreases transpiration about 20%.

WARMER AND DRIER WEATHER ALSO AFFECTS CROPS

If the calculations of meteorologists are correct, crops will encounter a warmer and drier environment as well as increased CO_2. The indirect effect of CO_2 upon crops via the "greenhouse" effect and changed weather can be estimated by the coefficients of multiple linear regression equations relating past weather and yields. These equations, which are associated with the name of Thompson (1969), were employed by Clarence Sakamoto to estimate the effect of a 1°C warming and 10% less rain. In a linear regression of the yield of wheat upon past weather, the coefficient for hot days is the change in tons of grain per hectare per hot day. For example, from the Red River Valley to Nebraska the regressions of wheat yields upon past weather have coefficients of about -0.003 T/ha per June day hotter than 32°C. For a 1°C warming and 10% less rain, the change in yields calculated from the equations from the Red River Valley to Oklahoma is 0.04-0.18 T/ha or 2-12% less wheat (Waggoner 1983).

The physiology of the crop and the physics of evaporation provide an alternative to history for predicting the effect of changed temperature and moisture upon yield. Duncan et al. (1967) combined this knowledge into a computer simulation of crop growth, and again, Clarence Sakamoto employed a simulator of spring wheat in North Dakota to calculate the effect of weather changes upon wheat yield. Unlike the calculation of one change in yield for a locality and the projected change in weather from the regression coefficients encapsulating many past years of weather and yield, the simulator produced a frequency distribution of yields because many past years of weather, with and without the projected changes, were fed into the simulator. The consequence (see Figure 1) of the changed weather was many yields and their frequency distribution skewed by a higher frequency of low yields and a decrease of 0.2 T/ha or 2 quintals/ha in the median. Although the simulated yields are lower than actual ones and the change in median yield is somewhat greater than the change calculated by the regression coefficients, the direction and magnitude of the changes are similar (Waggoner 1983).

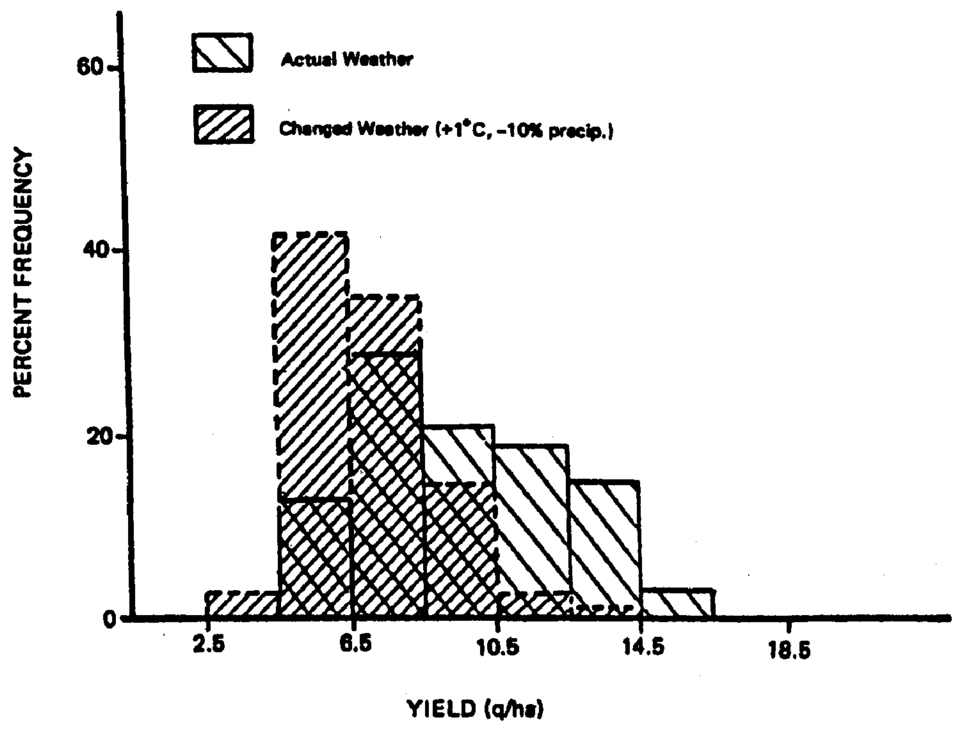

Figure 1. Simulated yields of spring wheat in North Dakota showing the possible effects of changed weather accompanying a rise in CO_2. The simulation used the actual weather during 1949-80 to calculate yields and then weather 1°C warmer and with 10% less rain. Ten quintals or q/ha equal a T/ha (Waggoner 1983).

COMBINED EFFECTS OF CO_2 AND WEATHER

In the end, the advantageous direct effects of CO_2 must be weighed against the net effect. In the United States, the predicted direct and indirect effects seem to cancel producing a net of zero. In more tropical places where little warming is predicted, the benefit of increased CO_2 upon photosynthesis would only be modified by changes in rain. At northern margins of crops, the warming of the greenhouse effect plus increased CO_2 seem likely to produce a net benefit regardless of rain.

Citing complications omitted from the simple calculations above is easy: Less irrigation water, shifty pests, expansion onto different soils at margins, change probability of extremes, and, in the end, ramifications of changed weather that can only be foreseen from anecdotal history.

Irrigation

In relative terms, the change in supply of irrigation water will likely exceed the change in rain. Because irrigation uses the small residue between rain and evaporation rather than rain itself, the relative change of irrigation water will logically be greater than the change in rain. For example, if runoff were 85% of rain, a 10% decrease in rain would decrease runoff by 10/15 or two-thirds. Although a decrease in transpiration caused by CO_2 narrowing stomata may moderate the expected change in runoff from a watershed supporting much foliage (Idso and Brazel 1984), the projected warmer and drier weather could substantially decrease the water, for example, in the Colorado River (Revelle and Waggoner 1983).

Pests

The ravages of pests can amplify the direct effects of CO_2, temperature, and humidity, changing yield disproportionately. A student of systems would say the pests made the effect of weather nonlinear. In Europe the Irish potato famine, caused by a mildew encouraged by wet weather, and in America the Southern corn leaf blight, caused by another fungus prospering in humid weather, exemplify amplified destruction by the combination of a new or shifty fungus and favorable weather. Worldwide, the attacks of locusts or grasshoppers exemplify insect pests that amplify the impact of weather (NAS 1976).

Margins

Parry and Carter (1984) addressed margins between two ecosystems or farming systems. They distinguished geographical marginality defined by physical factors; economic marginality where returns barely exceed costs; and social marginality where people are forced from indigenous resources into marginal economies. Although one can cite examples of all these, maps make geographical margins easy to visualize. Emanuel and Shugart (1984) mapped movement of Holdridge Life-Zones that might be caused solely by the warming from a doubling of CO_2. They show, for example, the northern boundary of the cool temperate steppe moving from the prairie provinces of Canada to central Alaska and the southern boundary of the cool temperate forest moving from Illinois to Wisconsin. Although such a map does not encompass changed rain and CO_2, it does show margins where a change in weather will cause nonlinear effects on crops. For example, an Illinois farmer may continue to grow corn with yields changing more or less proportionally with changes in weather, while a Wisconsin dairy farmer now growing silage may, however, become a grain farmer, experiencing a disproportionate change.

Their maps illustrate that land limits migrating margins. Thus crops of the dry warm temperate forest moving northward in proportion to the change in weather would encounter a nonlinear change when the migrating margins encounter the beaches of the Great Lakes. Although the margins of soil types are too subtle to incorporate into the maps, they too will affect movement of crops. For example, in the future fertile prairie soils formed in zones of moderate rain with a summer maximum might receive the rain of a steppe or forest.

Frequency Distribution of Rain

The regression coefficients relating past yields and weather show how many T/ha will be lost or gained in proportion to changes in the weather. Should the increments be subtracted from a trend of yields, from a regional average, or, as Perry and Carter (1984) suggest, from frequency distributions of yield produced by annual lotteries with the weather? Frequency distributions were illustrated above by simulated yields of spring wheat in North Dakota.

These are other reasons to focus on frequency distributions and probabilities instead of averages. The hardship of less food on the table or less money in the bank may grow keener in proportion to trends in average weather. The tragedies of famine and bankruptcies, however, are caused by falling below a limit or threshold.

Although the frequency distribution of the rain accumulated over a long time such as a year follows normal (Gaussian) distribution, frequency distributions of rain for shorter periods are squeezed by the limit of zero on the left and stretched by a few downpours on the right. Thus even in humid New Haven, Connecticut, the distribution of July rain is greatly skewed toward large amounts although the driest July in the 84 years had a full 22 mm, making the mean of 107 mm far above the mode of 72 (Figure 2). In dry Great Falls, Montana, the mean July rain of 34 mm is nearly three times the mode.

Recognizing that the normal distribution would not fit the skewed distributions of rain, Barger and Thom (1949) employed the gamma distribution function:

$$f(x) = x^{g-1} \exp(-x/b) \;/\; b^{g} \;/\; \mathrm{Gamma}(g)$$

The amount of rain is x mm, the scale is b mm, the shape parameter is g, and Gamma is the usual gamma function. The frequency f(x) per mm is 0 for x less than 0. If g is between 0 and 1, the mode is 0; and if g is greater than 1, the mode is b(g-1). The mean is bg, and the variance b^2g mm^2. Skewness is 2/(square root of g), smaller g increasing skewness. The fit of the gamma distribution function or f(x) to July rain in New Haven is illustrated in Figure 2.

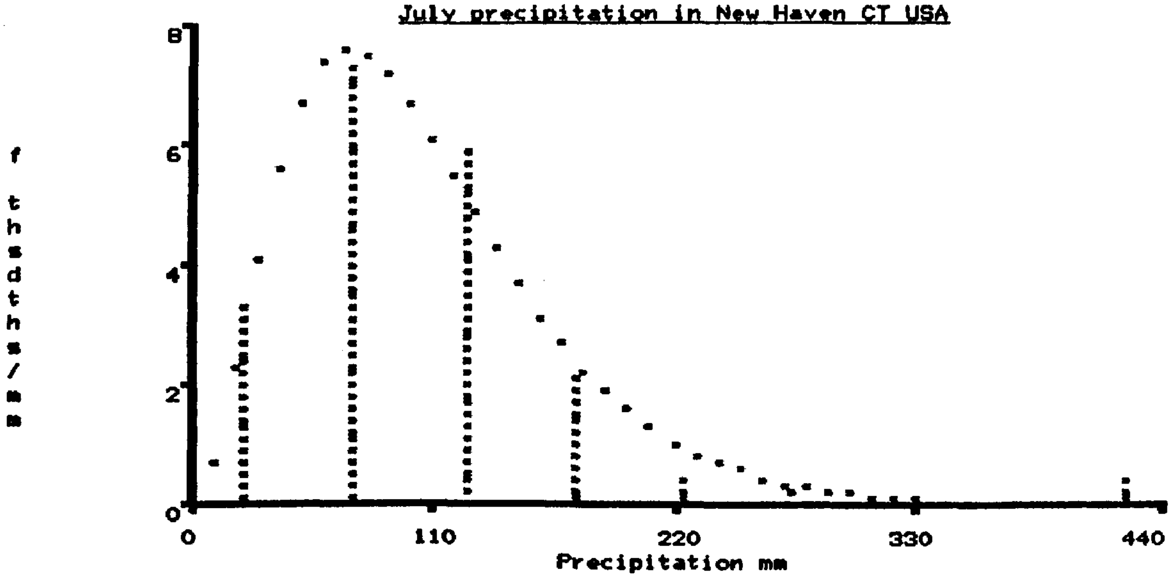

Figure 2. The fit of the gamma distribution function to July rain in New Haven.

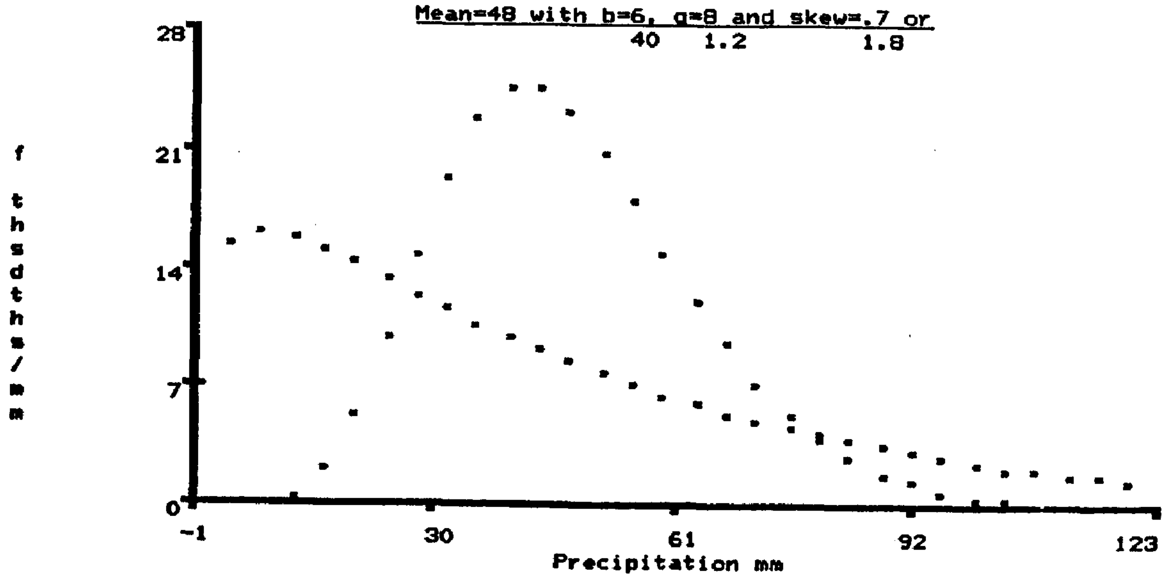

Figure 3. The parameters b and g of the gamma distribution illustrated by frequency distributions for two hypothetical rain climates, both with mean of 48. If g is 8 and hence skewness 0.7, the distribution of frequency f is nearly normal and the mode is 42. However, if g is 1.2 and skewness 1.8, the distribution is skewed to the right and the mode falls to 8.

The parameters b and g are illustrated in Figure 3 by the f for two hypothetical climates, both with mean rain of 48. If g is 8 and hence skewness 0.7, the distribution is nearly normal and the mode is 42. If g is 1.2 and skewness 1.8, however, the distribution is skewed to the right and the mode is only 8.

The probability F(x) that rain will be less than x mm is apt to capture the farmer's interest. Figure 4 shows that in the climate with a mean of 48 but a nearly normal distribution, the probability of less than 29 is about 0.1; whereas in the climate with the same mean but a skewed distribution, it is about five times as great.

The f of Figure 3 can now be seen in a new light. For example, in the normal distribution, f is the frequency 0.0163 per season of rain of 28.5-29.5 mm. The other meaning of f, however, is the increment per mm in the probability F in Figure 4. If we shift the limit of 29 by 1, the probability will change by f. Alternatively, if climatic change shifts the entire distribution by 1 mm, the probability F of less than 29 will change about f or 0.0163.

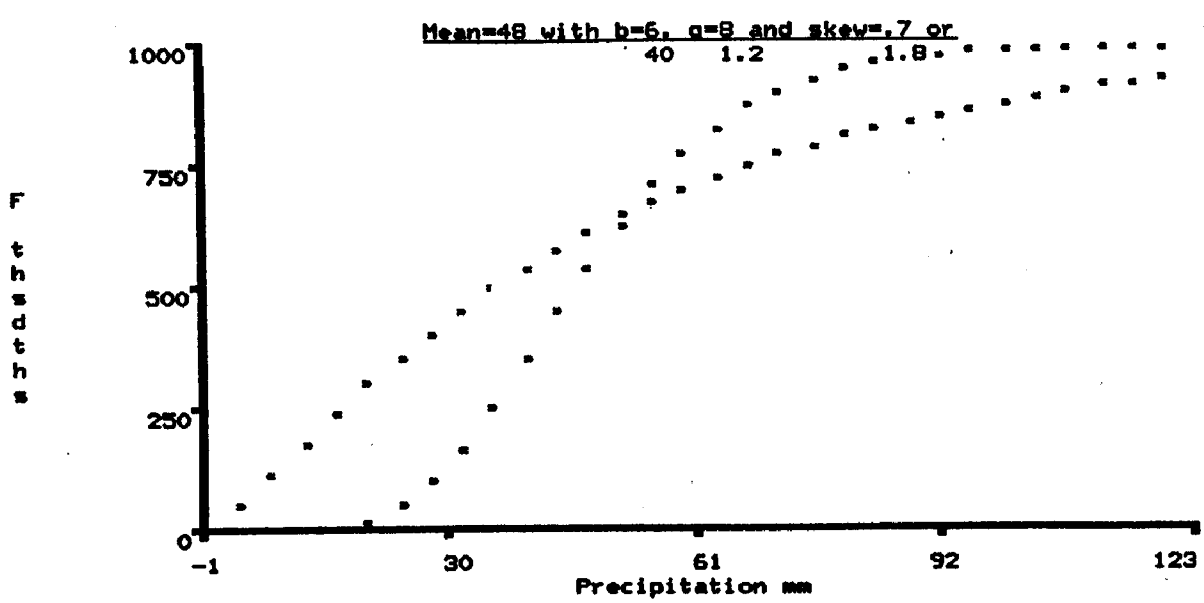

Figure 4. The probability F of rain less than a limit. In the climate with a mean of 48 but a nearly normal distribution, the probability of less than 29 is about 1/10 or .100. On the other hand, in the climate with the same mean but a skewed distribution, the probability of less than 29 is about .500.

A farmer may, of course, be even more interested in the relative change in the probability of drought. Is the 0.0163 change large or small relative to the present probability of Figure 4 to which he has adapted? Whereas the change in probability for 1 mm change in rain is approximately f, the relative change in probability is f / F. Because F is much less than 1 for critically small amounts of rain, the relative change f / F per mm in Figure 5 is larger than the absolute change f per mm in Figure 3. In the example, the relative change in probability of less than 29 is (0.0163/0.1170) = 0.14 per mm change in rain. Figure 5 shows that the relative change f / F is greater for more severe droughts than for less severe ones.

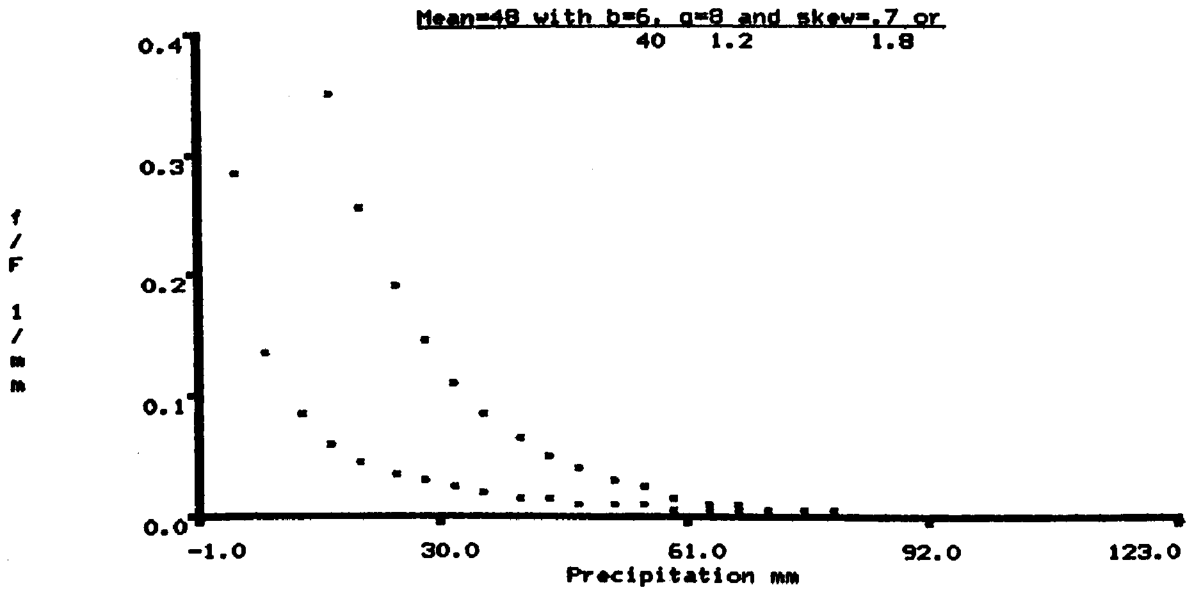

Figure 5. The relative change f / F in probability per mm change in rain. In the nearly normal distribution and upper curve of the figure, the relative change in probability of less than 29 is (0.0163/0.1170) or 0.14 per mm change in rain. In the skewed distribution with its greater probability F of less than 29, the relative change is less although the f's at 29 in Figure 3 are similar. The relative change f / F is greater for more abnormal droughts and less for more frequent ones.

A meteorologist may be interested in still another sort of change: What is the relative change in the probability of drought for a given relative change in the mean rain? This relative-relative change is (mean * f / F) dimensionless. Because the mean is normally much larger than 1, the relative-relative change (mean * f / F) is larger than the relative change f / F, which in turn is larger than the absolute change f. In the example, the change of probability of less than 29 is 0.0163 per mm, the relative change is 0.14 per mm, and the dimensionless relative-relative change is 48 times 0.14 or 6.7 [relative change in yield] / [relative change in rain].

Skewness affects these changes. Although the skewed distribution of Figure 3, produced by b=40 and g=1.2, has the same mean as the nearly normal distribution that we have been examining, it produces different changes. It has a probability of 0.424 of rain less than 29 instead of 0.117, and the farmer has adapted to drought. Although the change f is only slightly less for the skewed than for the nearly normal distribution, the relative and relative-relative changes are much less because the divisor F is larger. That is, compared to the nearly normal distribution, the skewed has an absolute change f of 0.0123 instead of 0.0163 per mm, a relative change f / F of 0.03 instead of 0.14 per mm and a relative-relative change (mean * f / F) of 1.4 instead of 6.7. That is, a 1-mm decrease in rain in the drier climate with a skewed distribution and higher probability of less than a given rainfall caused smaller relative changes in probability.

How Frequency Distributions Might Change

Having examined the distributions themselves, we can consider alternative ways that, say, a 10% reduction would occur. Each future month might have 90% of the former rain. Alternatively, the rain of each future month might be decreased by the absolute amount of one tenth of the mean. Although the alternative decreases of future rain would produce the same mean, the frequency distributions and probabilities would differ.

If the past July rain in New Haven is changed to 90% of the amount that actually fell in the month, the variance and mean are both decreased, and the probability of less than 25 mm rises from 0.031 to 0.042. If, however, a tenth of the mean rain, 10.7 mm, is subtracted from each past July rain, the variance is unchanged, skewness increases, and the probability of less than 25 mm rises from 0.031 to 0.070.

Different, present climates suggest which alternative might actually occur if rain decreases. Frequency distributions of rain during three weeks in April vary regularly along a transect from Alliance, Nebraska to Wooster, Ohio (Barger, Shaw, and Dale 1959). From drier to more moist, the mean increases by 60%, the variance scarcely changes and skewness decreases. Similarly, among 360 localities around the earth, the coefficient of variation increases as rain decreases below 500 mm (Conrad 1941). Thus the second scenario of steady variance and increasing skewness with decreasing rain seems more likely than variance and mean changing in step. That is, rain seems more likely to change by an absolute rather than a proportional amount.

This means, in the example of July rain in New Haven, that the 10% decrease would about double the probability of less than 25 mm, which is a relative change of 1.2 and a relative-relative change of 12.

To examine the effect of a 10% decrease in the July mean of dry Great Falls, 3.4 mm can be subtracted from each July with the proviso that none shall be decreased below 1. This increases skewness but scarcely changes the standard deviation. The probability of 5 mm or less is increased from 0.068 to 0.137. Because the July rain in Great Falls was decreased by only 3.4 instead of the 10.7 in New Haven and because I chose the critical amount of 5 instead of 25 for Great Falls, the relative changes are about the same in both localities.

Probability of Consecutive Dry Periods

Because consecutive periods of harmful weather may exhaust reserves and thus be disproportionately more harmful than single periods, the probability of consecutive events of less than a specified rain in a period gives another view of changing climate.

If the probabilities of, say, dry June and dry July, are F(1) and F(2), the probability of consecutive dry months is F(1^2) = F(1) * F(2) if the consecutive events are independent. Then the change of probability of the consecutive events is f(1)F(2) + f(2)F(1), and the relative change is f(1)/F(1) + f(2)/F(2), which is twice the relative change for a single event if the two distributions are the same.

Examination of New Haven and Great Falls shows no evidence that June and July rains are correlated. Thus the above reasoning about great relative changes in probabilities of consecutive events caused by small changes in climate is valid. For example, decreasing the rain of each June and July in New Haven by 5% of the mean only increases the probability of less than 50 mm in June from 0.21 to 0.27 and in July from 0.17 to 0.21. The probability of a dry June followed by a dry July, however, increases from 0.036 to 0.071; that is, the relative changes in probability are about 0.3 for June and July, individually, but for consecutive months the relative change in probability is fully 1.0. Because the relative change in rain is 1/20 and the relative change in probability is 1, the relative-relative change in probability of consecutive dry months is fully twenty-fold, which far exceeds even the large relative-relative change of six-fold in probability for June or July alone.

The highlights about frequency distribution and changes in climate can be summarized as follows:

- Although distributions of large amounts of rain such as annual sums are normal, the distributions of smaller amounts like monthly sums are skewed toward downpours and fitted by the gamma distribution function.

- The frequency per mm in a distribution is also the change in probability per mm change in rain, and the skewed distributions of, say, monthly sums have relatively high frequencies below the mean.

- While the frequency distribution of rain in a dry climate has a smaller mean than in a humid one, the drier often has no smaller variance and a greater skewness, suggesting a change to a drier climate may be caused by a decrease in each period of an absolute amount rather than a fixed percentage.

- The relative increase in probability of drought caused by a decrease in rain will be greater than the absolute change in probability and much greater than the relative change in rain, especially for abnormal droughts or for consecutive events like two dry months.

Frequency Distributions of Yield

Agriculturalists must, of course, relate climate to yield. Because extremes of yield rather than averages starve and bankrupt, frequency distributions must be examined here, too.

Past wheat yields are a heterogeneous population trending upward, especially since the 1940s. On the other hand, deviations of yield from a curvilinear trend are not distributed with significant difference from the normal function. Because weather and crops differ over the earth, yields are not perfectly correlated over a region, and there is no correlation at all between distant regions (Waggoner 1979). Thus the variance of regional annual means decreases as the size of the region increases, and for example, the variance of average annual yield of wheat in the United States is only about a quarter of that of Montana winter wheat alone. Thus, commerce moderates extremes.

How will the probability of a given yield change with a decrease each season in rain by, for example, mean/10? From 1910-72 both winter and spring wheat in Montana (adjusted to 1972) yielded 0.0025 T/ha less for each 1 mm decrease in the April-September rain. The estimate was obtained by relating yield to year, year^2 and rain in Great Falls and Miles City (correlation coefficient = 0.79). Because there is no evidence that the relation between rain and deviation from the trend in yield with time is not linear from 100 to 460 mm, I examined the consequences of a 10% or 25 mm decrease in rain by subtracting 25 mm x 0.0025 T/ha/mm or 0.0625 T/ha from each annual yield. The decrease is 3% of winter and 4% of spring wheat mean yield. This small decrease in yield is comparable to those calculated above by Sakamoto remembering that he included the effect of 1°C warming whereas the calculation for Montana did not.

When the relative and relative-relative changes in yield are calculated, a magnification occurs as when rain was analyzed. Thus the decrease in winter wheat increases the probability of, say, less than 1.6 T/ha from 0.045 to 0.067, which is a relative change of 0.6 and a relative-relative change of sixfold [relative change in yield] / [relative change in rain].

Three lessons are suggested:

- Mean yields vary less over a wider region than over a small one.
- A 10% decrease in rain may decrease mean yield much less than 10%.
- The probability of a given low yield may change relatively more than the mean, and the relative change in probability may be much more than the relative change in rain.

ANECDOTES FROM HISTORY SHOW THAT CALCULATIONS CAN BE NAIVE

Although the disproportionate responses of crops to changes in weather described above teach us that incremental changes in weather may cause surprising effects, calculation finally fails us because weather has so many ramifications within human affairs and our own reactions are so unpredictable and influential. Our recourse is history, and I shall illustrate by the Irish Famine as analyzed by Woodham-Smith (1962).

In the beginning of July 1845 the potato crop promised well, and the weather was hot and dry. The weather changed to gloom, a new mildew was present and a single crop, the potato, failed. More ramifications than the mildew of one crop were needed to transform gloomy weather into a decrease in the 1851 population of Ireland from the expected 9 million souls to only 6.5 million.

Between 1779 and 1841 the population had increased by 172%, encouraged by an incredibly cheap food, the potato introduced from America. Turf provided warmth, and miserable standards encouraged early marriage. Land had been divided and subdivided. The closely-packed population and frantic competition for land had been caused by the potato, and in 1845, the existence of the Irish people depended entirely on the potato, a productive but dangerous crop that could not bé stored from season to season. The stage was set.

Once the tragedy began to play, ramifications were incalculable. Religion as well as memory of conquest divided the Irish from a government in England that was passing through a financial crisis. The doctrine of laissez-faire made the government nervous that too much kindness to the Irish would corrupt them. The government did not assist with seed, did not encourage the growth of other crops, and required the hungry to give up all possessions and join the army of paupers to gain relief. Believers in free trade protected grain exports with soldiers without noticing that the traders were inexperienced in importing. Laws enacted in 1848 and 1849 forced the sale of estates on a depressed market, leaving owners impoverished, creditors penniless, and tenants with strangers for landlords. Typhus administered the coup de grace in Ireland, and immigrants carried the disease to England and America, where laws were enacted to increase the cost of passage, discourage destitute immigrants, and turn back the diseased.

History might have been different. Diverse crops, fewer people per acre, patient creditors, louse control, and imported food might have tempered the affects of the change in weather and yields. The ramifications of weather and human reactions illustrated by anecdotal history show that straightforward calculations are naive.

WHAT CAN AGRICULTURAL SCIENTISTS DO?

Although refining our estimates of the projected change and its impact are easy to suggest, these are spectator sports, and society may expect agricultural scientists to be participants rather than spectators.

Steady modification of varieties and amendment of soils, especially at the arid and northern margins of regions, is surely expected of these scientists. They may be expected to accomplish this continuously by annually exposing their experimental plots to the weather rather than by logically but slowly unraveling physiological mechanisms and engineering genes to adapt varieties and husbandry. They will be expected to quickly devise controls for shifting pests. Someone must understand the commerce that feeds, from new regions of suitable climate, the populations stranded in regions where the climate produces fewer crops. Agricultural scientists will surely be expected to aid rather than watch mankind's adaptation to an inexorable increase in CO_2 and its greenhouse effect.

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Drought Policy Implications of CO_2-Induced Climatic Change in the United States and Australia

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INTRODUCTION

Drought frequently affects portions of the United States and Australia and causes substantial economic loss, especially in the agricultural sector. Government has come to play a key role in both countries in attempting to mitigate the impact of drought. The organizational structure for responding to drought used by federal and state government in the United States has evolved gradually since the 1930s. Drought assistance is provided by federal government through a variety of emergency, short-term and long-term measures. States are not required to accept fiscal or administrative responsibility for drought assistance.

As a direct result of drought, the federal (Commonwealth) government of Australia faces problems similar to those in the United States. No part of Australia is free from drought, and most of the country suffers from frequent occurrences of severe drought (Foley 1957; Gibbs and Maher 1967; Reynolds, Watson, and Collins 1983). Only 22 of the past 100 years have been free of drought (Anonymous 1983). Much of Australia's agricultural land is in marginal rainfall zones where even a minor drought has immediate economic repercussions (Gentilli 1971; Heathcote 1967). Hence, Australian agriculture has been forced to make significant adjustments to its precarious situation.

The Australian government began to formulate drought programs in the 1930s. Both federal and state governments have been actively involved since then in the evolution of an organization to administer drought assistance programs. Although the philosophies behind Australian and United States drought policy are similar, the administration of particular policies differ considerably. Both have been the target of criticism from the scientific community, government officials, and recipients of relief.

This paper reviews, evaluates, and compares the drought programs and policies of state and federal governments in the United States and Australia. Emphasis is placed on governmental actions during recent episodes of widespread, severe drought--during 1976-77 in the United States and 1982-83 in Australia. Recommendations are offered for improving the capability of government in the United States and Australia to respond to drought. Finally, I speculate on the applications of CO_2-induced climatic change on the formulation of clear and concise drought policy objectives and plans.

THE OBJECTIVES OF DROUGHT POLICY

Drought policy has not been stated explicitly by government in either the United States or Australia. The underlying question is: should government be involved in providing assistance to those economic sectors or persons that experience hardship in times of drought? Because of the frequency, severity, and extent of drought in the United States and Australia, governments have elected to provide assistance through a wide range of measures. These measures are the instruments of a de facto policy that has evolved over the past 50 years of reacting to rather than preparing for periods of crisis. The decision of whether or not to provide aid has been based more often on political than economic reasoning.

Without clearly stated drought policy objectives, the effectiveness of assistance measures is difficult, if not impossible, to evaluate. I propose three objectives for drought policy. First, assistance measures should not discourage agricultural producers, municipalities, and other groups from adopting appropriate and efficient management practices that help to alleviate the effects of drought. Second, assistance should be provided in an equitable, consistent, and predictable manner to all without regard to economic circumstances, industry, or geographic region. Third, the importance of protecting the natural and agricultural resource base must be recognized. Although these aims may not be achievable in all cases, they do represent a model against which recent drought measures in the United States and Australia can be evaluated.

GOVERNMENT RESPONSE TO DROUGHT: THE UNITED STATES

Mid-1970s Drought

A recent episode of widespread, severe drought in the United States occurred in the mid-1970s. The years 1974, 1976, and 1977 stand out as those in which the greatest economic losses occurred. The impacts of drought during these years were most serious in the Great Plains and upper midwest states, as well as in the far west. Although the impacts were most critical in the agricultural sector, the municipal, industrial, and recreational sectors were also affected.

Mid-1970s Drought Policy and Assistance Measures

Although many programs are available to alleviate economic and physical hardship caused by natural disasters, only a few of these programs are designed specifically for drought. In 1976-77, sixteen federal agencies administered forty separate drought programs. The total funds allocated through these loan and grant programs during 1974-77, plus the costs of administering the programs, have been estimated at $7 to $8 billion (Wilhite, Rosenberg, and Glantz 1986).

Seven programs accounted for the vast majority of funds disbursed during the mid-1970s drought. The most important of these was the Farmers Home Administration's (FMHA) Emergency Loan Program. This program provided credit assistance to established farmers, ranchers, and agricultural operators when a natural disaster caused physical damage to property or resulted in severe crop production losses. During 1976-77 and the first eight months of fiscal year 1978, FMHA made more than 92,000 loans totaling $3.23 billion (General Accounting Office 1979).

A second major program of the mid-1970s was the Small Business Administration's (SBA) Disaster Loan Program. SBA was authorized to make necessary and appropriate loans to victims of floods, riots, civil disorders, and other catastrophes. Two types of loans are available through SBA: physical disaster loans and economic injury loans. Congress appropriated $1.4 billion for SBA to meet the demands of farmers (General Accounting Office 1979).

The Agricultural Stabilization and Conservation Service (ASCS), a subagency of the United States Department of Agriculture, administered the Disaster Payments Program. Under this program, a farmer whose production was reduced by natural disaster to less than two-thirds of his historical average production became eligible for payment at one-third of the target price level (ASCS 1976). The total amount of funds disbursed nationally is not known. However, in South Dakota, Nebraska, and Texas, this program provided more than $600 million in disaster payments during the period from 1974 to 1977 (Wilhite, Rosenberg, and Glantz 1984).

Other significant programs during the mid-1970s drought were the Emergency Fund and Emergency Drought Programs of the Department of Interior ($130 million), the Community Emergency Drought Relief Program of the Department of Commerce ($175 million), and FMHA's Community Program Loans and Grants ($225 million) (General Accounting Office 1979).

States in the United States do not have fiscal or administrative responsibility for relief measures under conditions of drought or other natural disasters. This responsibility has, since the 1930s, rested with the federal government. State governments have resisted attempts to bring them into the process (Wilhite, Rosenberg, and Glantz 1984). State arguments against cost-sharing on drought assistance measures has been based on limited resources and/or the inequality of available resources among states.

Evaluation of the Mid-1970s Drought Response

The mid-1970s federal and state response to drought in the United States has been documented and evaluated elsewhere (General Accounting Office 1979; Wilhite, Rosenberg, and Glantz 1984). The latter study demonstrated that governments in the United States often responded to drought through crisis management rather than through proactive programs. This was true not only in the mid-1970s but also in previous episodes of widespread and severe drought. In crisis management the time to act was perceived by decision makers to be short. Reaction to crisis often resulted in the implementation of hastily prepared assessment and response procedures that led to ineffective, poorly coordinated, and untimely response. The studies cited above suggest that if planning had been initiated between droughts, the opportunity would have existed to develop an organized response that might have more effectively addressed issues and impacts. The limited resources available to government to mitigate the effects of drought also might have been allocated in a more beneficial manner.

GOVERNMENTAL RESPONSE TO DROUGHT: AUSTRALIA

The 1982-83 Drought

The 1982-83 drought was confined primarily to eastern Australia, but portions of this area had been experiencing less severe droughts for a number of years. South Australia and New South Wales, for example, experienced droughts each year since 1976 and 1979, respectively (Reynolds, Watson, and Collins 1983). The droughts preceding 1982-83 increased the vulnerability of agricultural producers to additional severe drought.

The consequence of several consecutive years of drought in New South Wales was that the number of sheep declined from a peak of about 73 million in the 1970s to about 43 million in 1983. Cattle declined from a peak of 9 million in 1976 to about 4 million in 1983. The 1982-83 wheat crop was reduced from the normal 7 million to 1.5 million metric tons, a loss of approximately A$825 million (New South Wales Department of Agriculture 1983). The agricultural impacts of the drought in the other eastern states was similar in magnitude to that in New South Wales.

Recent Drought Policy and Assistance Measures

States have taken a more active role in responding to drought than American states have. Nevertheless, authority for federal involvement in natural disaster relief stems from Section 96 of the Australian Constitution, in which the federal government is empowered to make payments to the states on such terms and conditions as the Parliament determines to be appropriate (Department of Primary Industry 1984).

Before 1971, natural disaster relief and restoration was provided at a state's request by joint federal and state financing through a wide variety of arrangements. These financial arrangements were on a one-to-one cost-sharing basis. No limit was set on the level of funding that could be provided by the federal government.

In 1971 the Natural Disaster Relief Arrangements (NDRA) were established whereby states were expected to meet a certain base level or threshold of expenditures for disaster relief from their own resources (Department of Primary Industry 1984). Disasters provided for in this arrangement were droughts, cyclones, storms, floods, and bushfires. These expenditure thresholds were set according to 1969-70 state budget receipts and, therefore, varied between states. The original base levels ranged between A$5.0 million for New South Wales to A$0.7 million for Tasmania.

Under the NDRA arrangements, the federal government agreed to provide full reimbursement of eligible expenditures after the thresholds for state expenditures on natural disasters were reached. The NDRA formalized, for the first time, federal/state natural disaster relief arrangements. When NDRA was established, a special set of core measures, i.e., federal government-approved drought assistance measures, had evolved in each state on the basis of 30 years of government involvement in disaster relief. These measures were particularly relevant to the needs of each state because they had been designed by state government in response to their own disaster experiences. The formalization of NDRA in 1971 resulted in an increase in the number of core measures eligible in each state for reimbursement under this arrangement.

In June 1978 the Commonwealth government altered two features of the NDRA (National Drought Consultative Committee 1984). First, the state's base amounts were doubled because inflation had eroded the real value of the original thresholds and the number of measures eligible under these had increased. Second, the cost-sharing formula applied to reimbursements under the NDRA was changed to a three-to-one federal/state ratio for expenditures above the base amount. [Note: State base amounts under the NDRA agreements were increased significantly in 1984 following the 1982-83 drought. In most cases these amounts doubled the 1978 figures (Keating 1984).]

Table 1 shows the state expenditures for drought aid from 1970-71 to 1983-84 under the NDRA. The magnitude of these expenditures is significant, especially when compared to the limited financial responsibility of states in the United States. The governments of New South Wales, Queensland, and eastern Australia spent the most under these arrangements. The total for all states was just over A$570 million. Of this total, approximately A$180 million was spent during 1982-83 and A$120 million was spent during 1983-84.

Federal expenditures for drought aid under the NDRA arrangements during the period from 1970-71 to 1982-83 are shown in Table 2. During this period, payments to the states were just under A$370 million, or about A$200 million less than the total state expenditures. The largest share of the assistance was provided to Queensland and New South Wales. Federal expenditures on other natural disasters totaled about A$315 million. Queensland and New South Wales were again recipients of the largest accounts.

In addition to the cost-sharing measures described above, two federal drought assistance schemes were available during the 1982-83 drought. These included the Drought Relief Fodder Subsidy Scheme and the Drought Relief Interest Subsidy Scheme (National Drought Consultative Committee 1984). The Fodder Subsidy Scheme provided a payment to primary producers in drought-declared areas to help defray the cost of fodder for sheep and cattle. The administrative costs of this program were covered by the states. The amount of the subsidy was based on 50% of the price of feed wheat and the nutritive value of the fodder relative to wheat. The subsidy was payable on fodder purchased after September 1, 1982. This program was terminated on June 30, 1983. Fodder purchased after this date was not eligible for the subsidy. However, under the NDRA arrangements with the states, primary producers were allowed up to six months to submit claims after the June 30 termination date. Expenditures by the Commonwealth under this program were about A$104 million during 1982-83 and A$18 million through February of 1984.

The Drought Relief Interest Subsidy Scheme provided payments to eligible primary producers to cover all interest payments exceeding 12% per year. These

Table 1. Expenditures in Australian States Under Natural Disaster Relief Arrangements, by Type of Disaster, 1970-71 to 1983-84 (A$ Thousands) (National Drought Consultative Committee 1984)

DROUGHT								
	New South Wales	Victoria	Queens-land	South Australia	Western Australia	Tasmania	Northern Territory	TOTAL
1970-71	3,239	—	15,623	—	—	596	—	19,458
1971-72	458	—	3,143	—	—	—	—	3,601
1972-73	—	—	—	—	—	—	—	—
1973-74	987	—	—	—	—	—	—	987
1974-75	160	—	—	—	—	—	—	160
1975-76	—	—	—	—	—	—	—	—
1976-77	1,120	1,626	—	—	3,023	—	—	5,769
1977-78	2,620	1,228	2,785	13,580	17,999	—	—	38,212
1978-79	3,013	1,422	5,165	9,257	8,070	—	—	26,927
1979-80	—	—	2,208	2,225	12,560	—	—	16,993
1980-81	66,810	—	22,768	—	20,142	—	—	109,720
1981-82	31,018	—	9,608	—	5,081	295	—	46,002
1982-83	53,645	34,796	51,982	27,380	12,653	1,282	—	181,738
1983-84 (estimate)	21,500	8,100	63,300	4,600	22,100	1,900	—	121,500
Total	**184,570**	**47,172**	**176,582**	**57,042**	**101,628**	**4,073**	—	**571,067**

Table 2. Commonwealth of Australia Payments Under Natural Disaster Relief Arrangements, Estimated by Type of Disaster, 1970-71 to 1983-84 (A$ Thousands)
Source: National Drought Consultative Committee 1984

DROUGHT								
	New South Wales	Victoria	Queens-land	South Australia	Western Australia	Tasmania	Northern Territory	TOTAL
1970-71	450	—	13,632	—	—	16	—	14,098
1971-72	—	—	1,502	—	—	—	—	1,502
1972-73	—	—	46	—	—	—	—	46
1973-74	38	—	—	—	—	—	—	38
1974-75	114	—	—	—	—	—	—	114
1975-76	—	—	—	—	—	—	—	—
1976-77	779	716	—	—	2,134	—	—	3,629
1977-78	1,458	399	3,091	12,350	15,269	—	—	32,567
1978-79	743	173	2,942	5,430	6,036	—	—	15,324
1979-80	—	-229	1,224	-270	6,922	—	—	7,647
1980-81	42,447	—	14,780	-737	13,523	—	—	70,013
1981-82	14,554	—	5,162	—	2,239	267	—	22,222
1982-83	32,557	22,695	37,297	18,368	7,731	—	—	118,648
1983-84 (estimate)	11,800	4,600	45,300	4,300	15,300	600	—	81,900
Total	**104,940**	**28,354**	**124,976**	**39,441**	**69,154**	**883**	—	**367,748**

payments applied to loans taken out for primary production on or before August 31, 1982, and for carry-on purposes after that date. The states were responsible for receiving and verifying claims under this program. To be eligible, producers could not have available financial assets in excess of 12% of the total farm debt. This program was terminated on December 31, 1983, but producers were given 12 months to submit claims from the date their drought declaration was revoked or from the date of the termination of the scheme, whichever came first. Expenditures for the program, not including administrative costs, were about A$3 million in 1982-83 and A$23 million through February of 1984.

Evaluation of the 1982-83 Drought Response

The Livestock and Grain Producers Association (LGPA) of New South Wales strongly commended the state and federal governments of Australia "for their positive and cost effective drought assistance measures which so greatly contributed to the preservation of the national livestock base over recent years to enable a more rapid post-drought recovery" (Anonymous 1983). However, the Working Group for the Standing Committee of the Australian Agricultural Council (1983) concluded, "With the exception of congressional finance and information, existing policy measures, including those introduced during the current (1982-83) drought, do not perform well in achieving the objectives of drought policy which it considered important. In summary, the nearly $300 million of expenditures was not cost effective."

These contrasting views of the cost-effectiveness of recent drought measures in Australia reflect the controversy that currently exists over state and federal involvement in drought aid. Several other studies have been completed (National Farmers' Federation 1983; South Australian Department of Agriculture 1983; Stott 1983) and others are in progress (Minister for Primary Industry 1984; Australian Academies of Science 1984) to try to solve this issue. At stake is the future role that government will play in attempting to alleviate or mitigate the hardships caused by drought and, possibly, other natural disasters as well.

LGPA based its conclusions about recent assistance measures on the achievement of what it considers to be the first priority of drought aid in Australia--the preservation of the national sheep and cattle herd. Through the preservation of these resources, farm and nonfarm income was able to recover more quickly than after previous episodes of severe drought. LGPA estimated that, had government not intervened in 1982-83, 15 to 20 million sheep would have been slaughtered. As a result, post-drought recovery would have been delayed at a cost to the national economy of A$500 million over a five-year period (Anonymous 1983).

DROUGHT POLICY COMPARISONS

United States and Australian drought policies are compared in Table 3. The principal policy features are grouped into three categories: organization, response, and evaluation.

Organizational features are planning activities that provide timely and reliable assessments, such as a drought early warning system, and procedures for a coordinated and efficient response, such as drought declaration. These

Table 3. Comparison of Drought Policy Features: United States and Australia Status as of 1984

Features	United States	Australia
ORGANIZATION:		
National drought plan	None	Study in progress
State drought plans	In selected states	Through NDRA agreements
National drought early warning system	Joint USDA/NOAA Weather Facility	Bureau of Meteorology
Agricultural impact assessment techniques	Available, but generally unreliable	None available
Responsibility for drought declaration	Federal	State
Geographic unit of designation	County	Unit varies between states
Declaration procedures	Standard for all states, varies by program/agency	Varies between states; standard within states
RESPONSE:		
State fiscal responsibility for assistance measures	Negligible, if any	Defined by NDRA agreements up to base amounts, varies by state
State administrative responsibility for assistance measures	No responsibility for federal measures	Defined by NDRA agreements and by federal measures
Eligibility requirements and provisions of drought assistance measures	Standard within programs for all designated counties	Varies by state for NDRA core measures, standard for federal programs
National crop insurance program	All-risk federal program	Rainfall insurance feasibility study in progress
EVALUATION:		
Post-drought documentation and evaluation of procedures and measures	No routine evaluation by government	Routine evaluation by federal and state governments

characteristics would be the foundation of a national drought plan. Only a few states in the United States have drought plans (Wilhite and Wood 1985). State drought plans exist only in a loose form in Australia under the NDRA agreements.

Response features refer to assistance measures and associated administrative procedures that are in place to assist individual citizens or businesses experiencing economic and physical hardships because of drought. Numerous assistance measures are available in the United States but few are intended specifically for drought. Relief arrangements in Australia are, for the most part, included under the NDRA agreements. An all-risk crop insurance program has been evolving in the United States since 1939 (Federal Crop Insurance Corporation 1980). The Australian Bureau of Agricultural Economics is currently studying the feasibility of a rainfall insurance scheme. Hail and flood insurance is provided by commercial insurance companies in some areas.

Evaluation of organizational procedures and drought assistance measures in the post-drought recovery period is the third category of drought policy features. Governments in Australia have been more conscientious in their evaluation of recent drought response efforts. In the United States, government does not routinely evaluate the performance of drought response procedures or drought assistance measures. An evaluation of the 1976-77 drought response activities was made by the General Accounting Office (1979) at the request of the chairman of the Subcommittee on Environment, Energy, and Natural Resources, the late Congressman Leo J. Ryan. Wilhite, Rosenberg, and Glantz (1984) evaluated governmental response to the mid-1970s drought under sponsorship of the National Science Foundation. These were the first systematic evaluations of federal efforts to respond to drought in the United States.

For government in the United States to improve its drought assessment and response capability significantly, progress must be made in four key areas. The Australian experiences suggest that similar needs exist within their drought assessment and response system.

First, reliable and timely informational products (advisories, reports, management recommendations) and information dissemination plans must be developed. This has also been suggested as a high priority in Australia. For example, few can question the significance of more reliable and timely information about appropriate drought management strategies. Such information could reduce the effects of drought as well as the need for government assistance. Campbell (1973) has argued that Australian farmers have not exploited the available management strategies to their fullest. Government or the private sector should provide information to producers, not only about the relative costs and benefits of different management strategies, but also about the probability of droughts of various duration and intensity. Government must also more effectively inform potential recipients about the availability and provision of drought assistance measures.

Second, impact assessment techniques must be improved. In the case of agriculture, which is usually the first economic sector to experience hardships from drought, new tools must be developed to provide decisionmakers in government and business with the types of information needed to identify the onset and termination of drought and to better understand the severity of drought and its likely impact. These tools would be used by government to identify periods of abnormal risk and to trigger various assistance measures.

Third, designation procedures in the United States must be centralized under a single agency or committee with complete authority to determine eligibility for all assistance programs. Criteria must be determined before drought occurs and must be well publicized when drought occurs and applied consistently to all affected states, counties, and localities.

In Australia, the declaration of drought areas is a state responsibility, and procedures differ considerably between states. It may not be feasible to standardize procedures between the states because of the large precipitation gradients that exist over much of the country. In the United States, drought declaration decisions are a federal responsibility, considered at a state's request. Declaration procedures vary between agencies and, at times, between programs and within agencies. Drought policies on revocation of declarations must be better defined in both countries and take into account the lingering effects of drought.

Finally, assistance measures must be developed before drought occurs, i.e., a proactive approach must be taken to avoid the delays in program formulation and congressional approval that occurred in the United States during the mid-1970s. Programs should be administered by a single agency through the mechanism of an interagency committee in which federal agencies with responsibility in drought assessment and response are represented. Representatives of the affected states and/or regions should be included in the membership of this committee. Assistance measures must address the specific problems associated with drought.

Another question deserving considerable attention in the discussion of national drought policy is the degree of fiscal and administrative responsibility that states should have in support of assistance measures. The Australian approach of sharing the costs of these programs has been quite successful and may be applicable in the United States. Such an approach would allow states to have greater fiscal and administrative control over assistance measures. These measures could also be tailored to reflect the unique water supply problems and specific drought-related impacts of each state.

More attention should be directed to the development of assistance measures that encourage producers to incorporate appropriate levels of risk management in individual farm plans. Recipients of drought aid would benefit from knowing in advance what types of assistance will and will not be provided. Generally, Australians prefer assistance in the form of loans because recipients retain the flexibility to use the money in a way that best suits their farming situation; that is, farm management decisions remain with the farmer. Loans also have an important secondary effect: farmers can continue to spend at relatively normal levels and the economy of neighboring communities is not disturbed substantially. Equity requires that loans be made available to all. The Australian government has concluded that feed reserves and freight subsidies for water and feed can discourage adopting appropriate risk management techniques. These measures promote soil degradation by keeping livestock on the land during periods when the vegetation is severely stressed.

IMPLICATIONS OF CLIMATIC CHANGE ON DROUGHT POLICY

Recurring periods of severe drought frequently affect large portions of the United States and Australia. Past efforts by federal and state governments to respond to these events have been largely ineffective and poorly coordinated. Predictions of climatic change caused by increased concentrations of carbon dioxide (CO_2) and other gases, such as fluorocarbons, in the atmosphere are cause for concern. These predictions have been discussed extensively elsewhere (National Academy of Science 1982; Hansen, Volume 1; Manabe and Wetherald Volume 1.) These changes in climate may substantially alter existing regional water supplies, leading to an increased frequency in the occurrence of severe drought.

Many mathematical models have been used to predict the effects of increasing CO_2 and other trace gases on changes in the temperature and precipitation regimes of global and regional climates. For example, Manabe and Wetherald (1980) have used a model of global climate to test the effects of a doubling and quadrupling of the preindustrial carbon dioxide level. Their results can be summarized as follows. First, the temperature in the surface layers of the atmosphere will increase by about 3°C in the latitude zone from approximately 35° to 50°N. Second, precipitation will increase in the latitude zone between approximately 12° to 37°N and decrease in the zone from 37° to 50°N. Third, evaporation will increase slightly at all latitudes. Fourth, a net increase will occur in available water between 12° to 37°N latitude but a net decrease will occur between 37° to 50°N. Finally, minor changes in soil moisture will occur south of 37°N latitude but will decrease significantly in the latitude zone between about 37° to 47°N.

If these predictions are accurate, we can infer that much of the major food-producing areas of the United States, Europe, and the Soviet Union may become drier and less productive, while other areas may become wetter. A decline in available water supplies will be especially critical for marginal agricultural zones, e.g., the Great Plains of the United States. The message seems clear--some regions will be winners, others losers. However, regardless of the direction of the change, many economic sectors will be affected, including agriculture and forestry, transportation, energy, recreation, and health. In addition, these changes will influence the formulation of public policy and alter demographic patterns.

In Australia, as in the United States, the predicted climatic changes will be highly regional in character. The signs point to an increase in the intensity, duration, and southern penetration of the present summer rainfall regime, except along the southern coast, and to a decrease in winter rainfall in the southwest (Pittock 1983). The major agricultural regions of the south central portion of the country are expected to experience no change in current winter rainfall, and rainfall in the southeast may increase from 10% to 30%. These predictions may appear more favorable than they actually are since summer rainfall is of high intensity and results in high runoff. Evaporation rates during the summer are also quite high.

Large portions of Australia are considered marginal for agriculture. Therefore, any change in the current climate that results in a decrease in available water supplies will have substantially greater impacts on the economic sectors noted above than will occur in the United States with comparable changes.

SUMMARY AND CONCLUSIONS

The purpose of this paper is to compare recent drought policy in Australia and the United States and to offer recommendations for policy change in the United States. Four critical needs were identified: (a) reliable and timely informational products and dissemination plans that provide producers with better information about drought, alternative management strategies, and available assistance measures; (b) improved assessment techniques, especially in the agricultural sector, for use by government to identify periods of abnormal risk and to trigger assistance measures; (c) administratively centralized drought declaration procedures that are well publicized and consistently applied; and (d) standby assistance measures that encourage appropriate levels of risk management by producers and are equitable, consistent, and predictable. These measures must not discriminate against good farm managers. Although aimed at governments in the United States, most of these recommendations will be applicable to drought policy in other countries as well.

Governments in the United States have responded to drought by crisis management rather than risk management. This approach has been grossly ineffective. Several recent studies have addressed the issue of drought policy, or lack of it, in the United States and have concluded that we should now move toward drought planning with the aim of improving its efficiency. The development of a national drought plan is proposed as an effective way of implementing these recommendations in the United States. In Australia, two national drought committees are considering the benefits of a national drought policy that would be the basis for a drought plan. The U.S. National Climate Program has recently supported the establishment of a national drought plan (Board on Atmospheric Sciences and Climate 1986). A recent call for the development of national drought response plans has also come from the World Meteorological Organization (1986).

An appropriate question to ask at this point is: should we have a plan for dealing with the impact of drought? To answer that question, let us pose another question. Have previous approaches been successful? This question can be answered in terms of the drought policy objectives raised earlier in this paper. The first objective was to determine whether the current approach or policy encourages adopting appropriate and efficient management practices to insure against abnormal risk. It would appear that it does not. In fact, current policy often discourages wise risk-management decisions by producers. For example, tax incentives encourage the plowing of marginal land. When drought occurs, farmers often receive assistance for the losses of yield where such losses were inevitable.

The second objective was to determine whether drought policy in the United States is equitable, consistent, and predictable. Previous studies have shown that it has not been so. In fact, the opposite has been true of most drought response efforts. A national drought plan would help to rectify this situation by focusing attention on the policy objectives and on efficient means to achieve them.

The third objective was to assess whether the current approach recognizes the importance of protecting our natural and agricultural resources. The current approach appears to recognize the need, but assistance measures are often implemented in such an ineffective and untimely manner that this objective has not been realized. A national drought plan would promote greater recognition and preservation of natural resources.

A national drought plan would encourage states to take a more active role in planning for drought. In fact, drought planning should be coordinated between the states and federal government. In the past, most states have played a passive role, relying almost exclusively on the federal government to come to the assistance of residents of the drought-affected area. Although federal government has accepted this role, improving government response to drought requires a cooperative effort. States must develop their own organizational plans for collecting, analyzing, and disseminating information on drought conditions. Cost-sharing of drought assistance measures should be pursued as a means of involving state government in drought assistance.

The evidence presently available indicates that increasing concentrations of CO_2 and other gases are likely to result in changes in climate that will significantly alter regional water supplies, at times intensifying existing water management problems. For drought-prone regions, more logical and systematic planning for short-term, drought-related water shortages today may provide future generations with strategies that are appropriate for a new climatic regime.

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An Assessment of the Potential Economic Impacts of Climate Change in Oklahoma

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BACKGROUND

The State of Oklahoma has an area of approximately 177,816 km^2 (68,655 mi^2) and is located in the southern Great Plains region of the United States. It has a population of three million people and its economy is based on oil, natural gas, and agriculture. Major agricultural activities are livestock and winter wheat production. Other important agricultural commodities include sorghum, cotton, hay, and some corn. The average freeze-free period ranges from 181 days in northwestern Oklahoma to 217 days in southeastern regions. Precipitation ranges from 52 cm (20.42 in) in northwestern Oklahoma to 138 cm (53.75 in) in southeastern parts of the state. Currently, the region is suffering under unstable markets for both energy and agricultural products. A projected climate change (Hansen, Volume 1; Manabe and Wetherald, Volume 1) would cause additional stress which would have serious implications for the economic future of the state. Therefore, as part of our state-mandated mission, the Oklahoma Climatological Survey performs periodic analyses of the impact of weather and climate on food production systems (Cooter and Haug 1986). As climatologists we would like to be able to provide our clients with climate information that is relevant to their problems. In the present case, the agricultural community, or at least the agroclimatologists who represent the community, tell us what is "relevant" to them through the structure of their crop-yield models. The present analysis of potential agro-economic impacts resulting from a hypothetical change in the precipitation over Oklahoma will begin by describing the climate-change hypothesis, followed by a brief description of the crop-impact analysis models. Impacts on estimated production according to the model are presented, followed by more qualitative discussions of potential impacts from the hypothesized climate change on supplemental irrigation requirements, pest and pathogen losses, rate of maturity, and field work days. The summary concludes with recommendations for further research development. Although this analysis focuses on changes in precipitation, we plan to address temperature changes in future research.

CLIMATE CHANGE HYPOTHESIS

We begin by assuming that a representative hypothesis for the southern Great Plains is a 10% decrease in precipitation. Because we are most interested in agricultural impacts, we assume that this climate change occurs during the Oklahoma growing season, roughly April 1 through September 30. The next task is to determine how this 10% change might be distributed throughout the growing season. It is reasonable to assume that not every storm event will be modified by the same fraction since rainfall can result from a variety of environmental instabilities. As a first guess, observations of storm development and behavior in southwestern Oklahoma suggest the precipitation changes illustrated in Table 1, which assumes that storms exceeding 12 mm (0.5 in) would not be changed, while storms with less than 6 mm (0.25 in) would decline 30% to 50%. This hypothesis implies that those synoptic scale features that control southwestern Oklahoma's precipitation pattern will expand northward and eastward. If this categorical hypothesis is applied to each storm across the state over many growing seasons, anticipated precipitation changes range from a loss of 70 mm (2.75 in) in southeastern Oklahoma to 39 mm (1.52 in) in northwestern Oklahoma with an area weighted state precipitation change of 57 mm (2.21 in).

PRODUCTION IMPACT MODELS

Two types of agricultural crop-yield models were available to address the hypothesized climate change impacts. The first--and most widely used because of its modest data and computing requirements--is the statistical regression model. Regression models represent statistical modeling of past point or regional data. The second type of model is geophysical plant-process simulation, or a carbon-cycle model, so named because they are usually "driven" by the photosynthetic process. Plant process models are designed to mathematically simulate physical processes of plants. Although these relationships derive from or may be verified by field or laboratory observations, they are not bound to existing or past conditions and, given existing soils and crop varieties, are able to respond in a realistic fashion to new environmental conditions. Plant responses to altered levels of any given atmospheric constituent could be used in similar models by analyzing data collected in growth chamber experiments. Verified plant process models were not available for all of the selected study crops; therefore, a family of plant process and regression models was assembled. The selected crops and the models used in their analysis are presented in Table 2.

Each regression model predicts crop yield as a function of time, technology, and weekly weather at predetermined dates of critical phenological stages. Cultural and technological influences are assumed to be contained within trend and error terms. Thus, once the model has been constructed, the only inputs required for executing the model are weekly averaged weather. The plant process models are somewhat more complex, which is reflected in the number and detail of required input (see Table 3). The model estimates crop yield in terms of total biomass and grain. In addition, the model estimates dates of critical growth stages. Input data are readily available across the United States, and reliable yield and phenology estimates have been made using these models on scales as large as the U.S. corn belt. For instance, 1985 corn belt production estimates were within 5% of final USDA figures. Estimates of critical phenological events such as silking and maturity were

Table 1. The Distribution of a 10% Decrease in Growing Season Precipitation by Storm Category

24-Hour Precipitation	Precipitation Decrease
April, May, and June	
rain $\leq$ 6 mm	50%
6 mm < rain $\leq$ 12 mm	25%
rain > 12 mm	No Change
July, August, and September	
rain $\leq$ 6 mm	30%
6 mm < rain $\leq$ 12 mm	25%
rain > 12 mm	No Change

estimated to be within one week of observed values across the region (Botner et al. 1986).

WEATHER INPUT DATA

The weather data selected for use in this analysis between 1960 and 1984 are from the National Weather Service cooperative observing network. These are daily data which include maximum and minimum temperatures and 24-hour precipitation (Sladewski 1986). Daily observations of solar radiation which are required by the plant process models are not available from this data set and therefore were simulated using a statistical solar radiation generator (Hodges, French, and LeDuc 1983), based on the work of Richardson (1982). Soil moisture, which is required by the cotton regression model, was estimated using the process model soil water budget (Jones and Kiniry 1986). Seventy-seven weather data locations were selected across the state, one site to represent each of Oklahoma's seventy-seven counties.

MODEL RESULTS AND ANALYSIS

The potential impact of the hypothesized change in rainfall on crop production is simulated by altering 24-hour precipitation at each county location. All other weather inputs remain as before. For each season and each year, the difference between modeled crop yield under natural and

Table 2. Study Crops and Direct Impact Models Used to Assess the Potential Impact of a 10% Change in Growing Season Precipitation on Food and Fiber Production in Oklahoma.

CROP		MODEL
Winter Wheat		CERES - Wheat J. T. Ritchie and C. A. Jones Institute of Water Research Michigan State University East Lansing, Michigan
Corn		CERES - Maize C. A. Jones and J. R. Kiniry Texas A&M University Press College Station, Texas
Sorghum		$\hat{DY} = 2004.6 + 276.7 * PPT24 + 372.4 * PPT34 - 33.6 * TEMP35 + 318.6 * PPT36$
	where:	$\hat{DY}$ = estimated detrended yield (kg/ha) PPT24 = weekly precipitation for week 24 (planting) PPT34 = weekly precipitation for week 24 (heading to dough) TEMP35 = weekly average temperature for week 35 (dough) PPT36 = weekly precipitation for week 36 (dough)
Hay		$\hat{DY} = -0.40 + 0.34 * PPT27 + 0.27 * PPT33$
	where:	$\hat{DY}$ = estimated detrended yield (mt/ha) PPT27 = weekly precipitation for week 27 (2nd cutting) PPT33 = weekly precipitation for week 33 (3rd cutting)
Cotton		$\hat{DY} = -82.6 + 41.1 * SM28 - 56.1 * PPT45$
	where:	$\hat{DY}$ = estimated detrended yield (kg/ha) SM28 = soil moisture for week 28 (planting) PPT45 = weekly precipitation for week 45 (boll opening)

Table 3. Plant Process Model Input

SOIL PARAMETERS:

Soil Albedo
Stage 1 Soil Evaporation Coefficient
Drainage Coefficient
Runoff Curve Number
Soil Layer Thickness
Soil Water Contents
Root Distribution Weighting Factor

WEATHER PARAMETERS:

Daily Maximum Temperature
Daily Minimum Temperature
Precipitation
Solar Radiation

GENETIC PARAMETERS:

Growing Degree Days from Seedling Emergence to End of Juvenile Phase
Photoperiod Sensitivity Coefficient
Growing Degree Days from Silking to Physiological Maturity
Potential Kernel Number
Potential Kernel Growth Rate

OTHER CULTURAL PARAMETERS:

Fertilizer
- rates
- form
- depth
- dates of application

Irrigation
- rates
- method
- dates of application

Pesticide or Herbicide
- type
- rate
- method of application
- dates of application

Cultural Practices
- sowing date
- plant population
- sowing depth

modified precipitation regimes is declared to be the direct impact of climate change on yield. This difference is multiplied by the harvested acreage in the county that the weather station represents, to determine the impact on production levels. County production is then multiplied by the average crop price of the 1984 season to arrive at the direct impact (in dollars) on each commodity during a specific growing season. Figure 1 depicts the potential total direct impact in dollars of precipitation changes on all five study crops during one season, 1981. It also depicts the geographic distribution of precipitation modification impacts in hundreds of thousands of dollars. The contours represent smoothed estimates of county production value changes across space. If we assume that each county is roughly 2,590 km^2 (1,000 mi^2) in area, then the value at any point on the contour represents the potential impact of precipitation modification on an area of 2,590 km^2 (1,000 mi^2) surrounding the point. For example, a contour value of 5.0 represents a production loss of $500,000 per 2,590 km^2 (1,000 mi^2).

This procedure is repeated for each year between 1960 and 1984. The result is a distribution of potential direct impacts to agriculture on the Oklahoma economy under 1984 cultural practices, technology, crop varieties, and commodity prices, and throughout 25 weather years; the impacts are summarized in Table 4, which indicates that the largest impacts on yields would be in winter wheat [mean annual impact of 325 kg per ha (5 bu per ac)]. As a result of the extensive wheat acreage in Oklahoma, winter wheat also sustains the largest production value impact. A preliminary examination of expected price response to an average annual decrease of nearly 703 million kg (26 million bu) of wheat suggests only slight increases in wheat prices [price behavior per 2,703 million kg (100 million bu) change in supply taken from Womack (1980)]. On the average, under the stated climate change hypothesis and over 25 model years, a direct impact loss of $90.44 million to the State of Oklahoma can be expected. Losses for a particular year could range from $39 million to $158 million.

The potential impacts of climate change on specific agricultural activities such as irrigation water demand can also be addressed. In the simple example completed for this analysis of four far western counties which irrigate corn, we computed an average growing season irrigation increase of 5.2%.

Other potential agricultural impacts are more difficult to quantify than weather-determined crop yield and irrigation requirements. These include changes in pest or pathogen activities, crop maturity rates, and field work days.

In the case of both pests and pathogens, damage is usually greatest when plants are in a stressed or weakened condition. Rainfall changes at certain critical times during the growing season could increase plant vulnerability to infestation by increasing plant moisture stress, which would be important to irrigated as well as dryland agriculture. Irrigated fields provide a haven for weeds and pathogens which thrive when such fields are flooded or sprayed (Hatfield and Thomason 1982). Irrigation decreases canopy temperatures, increases soil moisture, and, consequently, increases the likelihood of pest and pathogen infestation. A climate change could increase the necessity for flooding and spraying. By increasing the number of these supplemental applications, damage resulting from pests and weeds may be increased. In

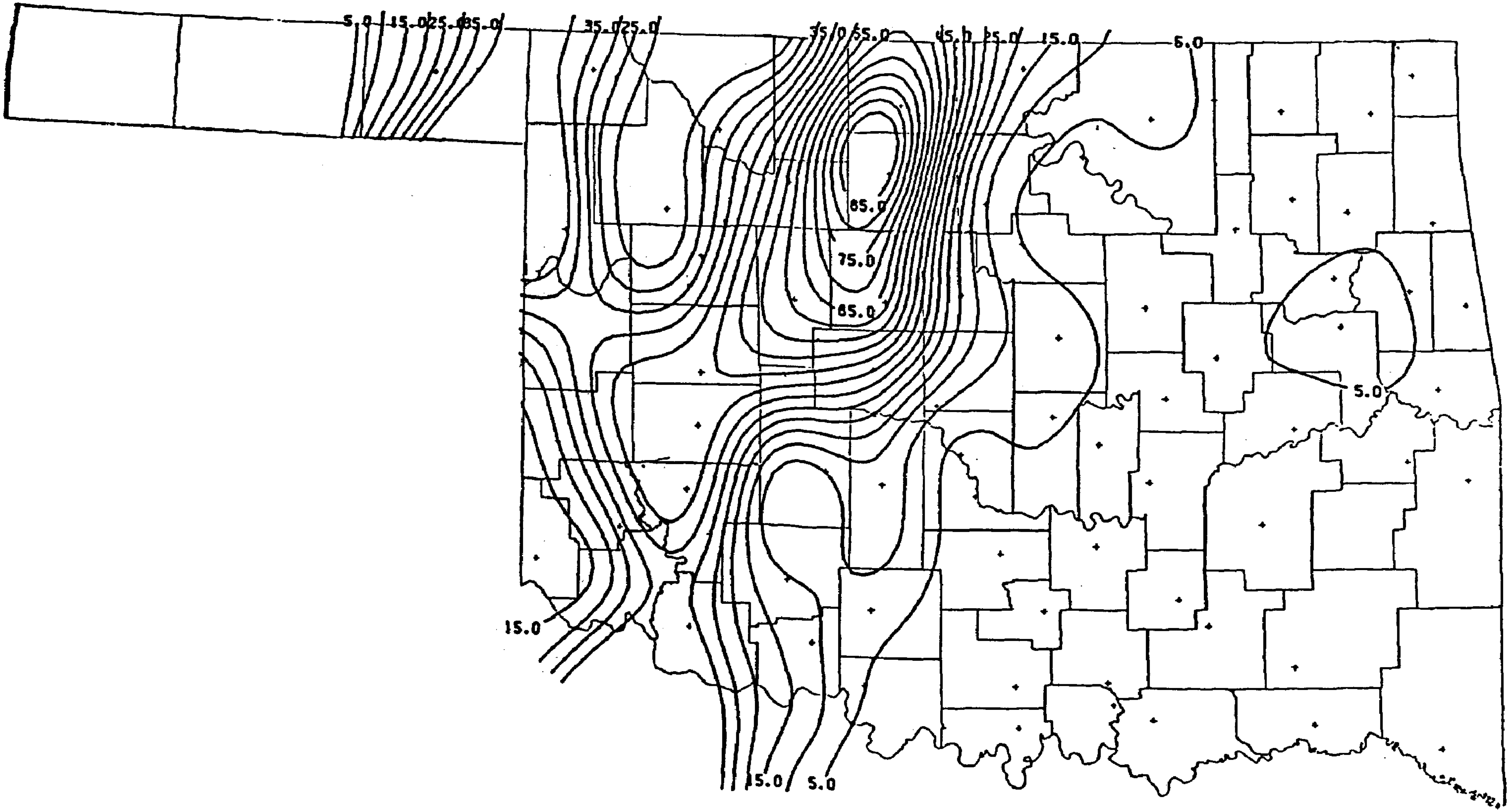

Figure 1. Potential direct negative impacts of a 10% decrease in growing season precipitation on 1981 Oklahoma production value of wheat, corn, sorghum, hay, and cotton in hundreds of thousands of dollars per county (after Cooter and Haug 1986).

Table 4. Potential Direct Impacts (Losses) Resulting from a 10% Decrease in Growing Season Precipitation on Oklahoma Crop Production (1984 Acreage and Price, 25 Weather Realizations) (After Cooter and Haug 1986).

CHANGES IN YIELD

	Wheat		Sorghum		Cotton		Hay		Corn	
	kg/ha	bu/ac	kg/ha	bu/ac	kg/ha	lbs/ac	mt/ha	tons/ac	kg/ha	bu/ac
mean	-324	-4.9	-64	-.9	-3	-2.6	-.02	-.01	-558	-8.9
s.d.	-125	-1.9	-21	-.3	-1	- .8	-.02	-.01	-545	-8.7
median	-343	-5.1	-63	-.9	-3	-2.4	-.02	-.01	-531	-8.4
maximum	-576	-8.6	-99	-1.5	-5	-4.4	-.04	-.02	-1710	-27.3
minimum	-133	-2.0	-29	-.4	-1	-1.3	0	.00	+326	+5.2

CHANGES IN PRODUCTION

	Wheat		Sorghum		Cotton		Hay		Corn	
	10^3 mt	10^3 bu	10^3 mt	10^3 bu	10^3 mt	10^3 lbs	10^3 mt	10^3 tons	10^3 mt	10^3 bu
mean	-698	-25758	-12	-427	-448	-985	-14	-15	-11	-445
s.d.	-268	-9911	-10	-373	-143	-314	-11	-12	-11	-434
median	-738	-27242	-11	-418	-417	-917	-18	-19	-11	-420
maximum	-1239	-45739	-18	-666	-745	-1660	-35	-38	- 9	-363
minimum	-286	-10547	- 5	-198	-215	-473	0	0	+ 7	+260

VALUE OF PRODUCTION CHANGES (1984 Prices)
(Million of Dollars)

	Wheat	Sorghum	Cotton	Hay	Corn
mean	-86.3	-1.1	-.5	-1.3	-1.4
s.d.	-33.2	- .9	-.2	-1.0	-1.4
median	-91.3	-1.0	-.5	-1.6	-1.3
maximum	-153.2	-1.7	-.8	-3.2	-4.2
minimum	-35.3	- .5	-.2	0	+ .8

TOTAL DIRECT IMPACTS
(Million of Dollars)

mean	-90.4
s.d.	-32.9
median	-96.9
maximum	-158.0
minimum	-39.2

response, the number, strength or quantity of herbicide and pesticide applications could also change.

The precipitation efficiency (the amount of water available for direct plant use) is also important. This measure is determined by the degree to which rainfall penetrates through the plant canopy and its subsequent infiltration into the soil. Under our climate change hypothesis, heavy storms that result in runoff are not affected. Light rains, up to 6 mm (.25 in) in 24 hours, are greatly affected. This could be detrimental in two ways. First, very light rainfall (trace to 1 mm) on a well-developed plant canopy usually does not reach the soil surface before absorption or evaporation takes place. There may also be beneficial cooling; but in general, these rains increase canopy humidities without much direct benefit to the plant. A 30% to 50% reduction in precipitation would imply that more of the light rain storms would be too light to increase soil moisture.

The development and spread of pathogens could also change. Very light rainfall (and even heavy dew) creates the kind of humid environment that is conducive to pathogen development. A heavy rainfall can deter development by knocking or washing fungal spores from the plant leaves. Lighter rainfall could thus increase the duration of conditions favorable for pathogen growth and development. The result would be an increase in the rate of successful establishment and spread of pathogen populations.

The potential impact of climate change on the rate of crop development cannot be addressed directly in this analysis. The plant process models could be used if temperature change information were available. The estimated impact of increased temperatures would differ for various thermal unit models. With a model that is simply a deviation from a fixed base, the increase in thermal time (and subsequent decrease in calendrical time) could be linear. With more sophisticated thermal unit models, the rate of crop development would progress on a sliding scale that peaks at some optimal temperature and decreases to either side. One benefit from lengthening growing seasons is a decrease in the likelihood of early or late frost damage. Oklahoma fruit crops are occasionally damaged by late spring frosts. Crops harvested in the fall, such as cotton and corn, sometimes suffer losses as the result of early fall frosts.

The final indirect impact of a modified precipitation regime to be considered here is change in field work days. Although a variety of conditions can influence whether a day is available for field work or not, this study considers trafficability as represented by soil moisture to be the dominant factor. Under the present hypothesis, no change in field-day availability is expected to result from changes in the number of rainfalls. Only historical rainfalls are modified. A field work day is defined as one in which soil moisture (as computed by the plant process models) is at 80% or less of water capacity available to the plant. A crop moisture budget was run at selected stations across the state, with and without climate change. The difference in the number of work weeks between the two budgets at a particular location represents the potential impact of climate modification on field days. Results indicate that one would expect an increase of from three to seven work days per growing season. Whether these impacts are economically significant and if they are benefits or disbenefits remains to be seen (Cooter and Haug 1986).

Up to this point, our analysis has dealt primarily with the assessment of the direct impacts of hypothesized climate change on Oklahoma's agricultural economy. These are impacts that can be measured directly in terms of commodity, such as dollar changes in the quantity of food, fiber, or energy produced or consumed. There are other impacts as well, which are called indirect, or stemming-from, effects. These effects can be assessed through the use of an input/output (I/O) economic model. I/O models generally consist of transaction matrices, which are tabular statements of the dollar value of production, and the "trading relations" among the various sectors of the regional economy. "Multipliers" for changes in sectoral transactions can be derived that estimate the impacts upon the economy when changes in natural resource supplies affect the production of other sectors of the economy. The model can be used to relate the producing sectors systematically to the resources and the consumers on the economy (Grubb 1960). The input/output model selected for use in this analysis is taken from Little and Doeksen (1968) and was applied in W. Cooter (1984).

Two types of multipliers were developed by W. Cooter (1984) to address the crops modeled in the present study. The first are called Type I Multipliers and represent the impacts for a $1 change in production for crops processed by the local crop-processing sector. These crops include winter wheat, corn, sorghum, and cotton. Type II multipliers represent the impacts of a $1 change in crop production for crops sold as feed or forage to the livestock sector. Hay production changes would utilize Type II Multipliers.

Table 5 summarizes the indirect economic components. Each mean is the potential long-term (24-year) average annual costs (losses) arising from hypothesized climate change precipitation modification given that each year's weather occurred while the agricultural sector employed 1984 crop varieties, acreage, and technology. Table 6 summarizes the state-level findings of this study.

Table 5. Average Annual Indirect Impacts (Losses) Attributed to a 10% Decrease in Growing Season Precipitation (After Cooter and Haug 1986).

	Agriculture Output (mill.$)	Final Demand (mill.$)	Personal Income (mill.$)	Gross Taxation (mill.$)	State Product (mill.$)
mean	327.7	176.9	113.4	20.8	171.5
s.d.	121.3	65.6	41.9	7.7	63.5
median	342.6	185.3	119.2	21.4	179.7
maximum	577.2	311.7	200.1	36.5	302.3
minimum	141.5	76.1	48.5	9.3	73.8

Table 6. Summary of the Average Annual State-Level Potential Direct and Indirect Impacts Resulting from a 10% Decrease in Growing Season Precipitation on the Oklahoma Economy.

Impacted Sector (Activity)	Average Annual State Level Impacts
Precipitation (area weighted)	- 57 mm (-2.21 inches)
Winter Wheat	- $86,240,000
Corn	- $1,380,000
Sorghum	- $1,090,000
Cotton	- $480,000
Hay	- $1,270,000
Pest and Pathogen Damage Control	*
Rate of Maturity	0
Field Work Days	+3 to +5 days
Irrigation Costs	+ $45,441 **
Irrigation Applications	+ .40 **
Irrigation Water Demand	+.41 ac-in **
State Output	- $327,700,000
Final Demand	- $176,900,000
Personal Income	- $113,400,000
Taxation	- $20,800,000
Gross State Product	- $171,500,000

* qualitative analysis only
** small region analysis

RECOMMENDATIONS FOR FURTHER RESEARCH

Further studies using plant process models to assess potential direct and indirect impacts of hypothesized climate changes are clearly warranted. A logical first step would be the incorporation of General Circulation Model (GCM) estimated weather inputs. The advantage of using these data is the additional confidence in the physical "sense" of the precipitation and temperature changes which the models utilize it provides. The GCMs also have the capability to produce radiation estimates which would be valuable in many plant process models. However, some roadblocks are perceived with some GCM products. Such roadblocks are space resolution (the GCM data are, at present, produced on too large a grid to be input "as-is" to plant process models) and the lack of maximum and minimum temperature estimates. Both of these objections can be, and in some cases have been, overcome through the supplemental use of a variety of statistical modeling techniques.

CONCLUSIONS

This research demonstrates the value of plant process models to a regional climate change assessment. Using these models for winter wheat and corn, as well as regression models in the cases of hay, cotton and sorghum, we estimate that a 10% decrease in total growing season precipitation could result in average annual direct losses to the Oklahoma economy of $90.44 million. Over 25 model years, losses could range from $39.2 million to $158.0 million. When indirect impacts are included in the analysis, we estimate that, on the average, gross state product could be reduced by $171.5 million, ranging over a 25-year period from $73.8 to $302.3 million. Impacts of climate change on irrigated agriculture do not appear (in this analysis) to play a significant role. Field work days also do not appear to be significantly affected by the hypothesized precipitation changes. Pest and pathogen losses and changes in rates of crop maturity can be expected but have not been quantified. Even without these latter two impacts, we have demonstrated that a 10% change in growing season precipitation could result in severe stress on the economy of the State of Oklahoma. In view of the possible magnitude and variability of these impacts, the development of policy alternatives, in conjunction with improved estimates of reasonable environmental futures and expected plant responses, would seem to be appropriate.

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Climatic Change—Implications for the Prairies

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ABSTRACT

This paper describes the impact of possible climatic change resulting from increased CO_2 warming on estimated dry matter yields for spring wheat crops in Saskatchewan, Canada. Data generated by the GCM modeling experiments at the Goddard Institute for Space Studies (GISS) for a doubling of atmospheric CO_2 concentration are compared to the 1951-80 climate norms. Climate change projected by the GISS model would increase the annual temperature in Saskatchewan by an average of 4.7°C and precipitation by 15%. The growing season length would be increased by an average of 48 days, advancing the beginning of the growing season by about 2 to 3 weeks and extending the fall harvest by about 3 to 4 weeks. Precipitation during the growing season would be increased by an average of 15%; however, analysis using the Palmer Drought Index suggests that Saskatchewan would become more drought-prone. The impact on yields is estimated using a generalized crop growth model by modifying the temperature and precipitation input data in relation to the 1951-80 norms period. Results suggest that, in the absence of direct CO_2 effects, production in Saskatchewan would be reduced by 16% to 26%. Assuming a 15% increase in photosynthetic capacity as a direct effect of doubling of CO_2, in addition to the increase in temperature and precipitation, production would still fall by 6% to 15%. Any decrease in precipitation from current levels would significantly reduce yields and production. To avoid midsummer drought, farmers are likely to shift to fall-sown crops.

INTRODUCTION

As long as man has cultivated crops the returns on his endeavors have been subject to the vagaries of weather and climate. The last few years certainly demonstrate this feature with regard to drought impacts on the prairies. For example, the devastating drought in 1985 has been estimated by Tung (1986) to have cost prairie farmers $231 million in terms of cash receipts from the loss in crop production and to have increased feed costs and destocking of beef cattle. Cash receipt losses carried over into 1986 and 1987 are expected to add a further \$545 million and \$53.2 million, respectively, for a total cost of approximately \$829 million. The "dirty thirties" (1933-37) and 1961 are other notable years when the vagaries of weather severely affected agriculture and the economy in the prairies. These year-to-year variations are for the most part random and generally unpredictable. They are part of the normal cycle of weather events forming the basis for the agricultural zonation of crops we see in place today--for example, the hard spring wheat crop that currently dominates prairie agriculture. This crop has been bred for and is well adapted to the prairie region.

Wheat is the most important cereal grain crop in the prairies and indeed in Canada. It is grown more extensively and produced in greater quantity than any other crop. Total harvested area of wheat in the prairies in 1984 was 12.8 million hectares and total production was 17.5 million tons. Saskatchewan produced 9.6 million tons, Alberta 4.3 million tons, and Manitoba 3.6 million tons (Saskatchewan Agriculture 1985). The dollar value of this crop in terms of cash receipts was worth \$3.89 billion to the prairies and exports of this crop contributed approximately \$2.3 billion to Canada's international balance of trade. The importance of wheat to the prairie region and to Canada as a whole certainly justifies an examination of the possible effects of climatic change on prairie wheat production.

Long-term climatic changes that produce distinctively different climatic regimes from the current norm may have significant influence on crop yields and subsequently on the geographic zones in which crops can be grown (Bootsma et al. 1984; Parry, Carter, and Konijn 1984). Such a change could result from the increase in carbon dioxide (CO_2) concentration in the atmosphere which has been occurring at a fairly rapid rate since the beginning of the Industrial Revolution in the 1860s (Keeling et al., 1976a, 1976b). A growing consensus, supported by a number of studies investigating the effects of increasing atmospheric CO_2 concentration, is that a general warming in the global climate can be expected (Manabe and Wetherald 1980; Manabe and Stouffer 1980; Mitchell 1983; Hansen et al. 1983).

The projected warming for a doubling of CO_2 which varies from 1.5°-4°C (Bach 1986) could have major repercussions for agriculture. For example, it has already been estimated in the United States that a 1°C temperature increase would shift the corn belt 175 km further northeast (Newman 1980); a similar shift in Canada is postulated by Bootsma et al. (1984). Williams (1975a, 1975b) and Williams and Oakes (1978) have estimated similar effects for wheat and barley in the Canadian prairies. More recently, Rosenzweig (1984) has examined the change in crop zonation in the North America wheat belt as a consequence of a possible doubling of CO_2 concentration. Rosenzweig's results suggested that the northern boundary of the winter wheat belt, which currently parallels the mean minimum January temperature of -13°C in the United States, would shift north and east into Canada.

Outside of the work by Bootsma et al. (1984), Blackburn and Stewart (1984) and Williams et al. (1986), little has been done to investigate the impact that climatic change might have on yields in Canada. This paper attempts to examine this question, looking at the potential impact on spring wheat production in Saskatchewan. Results presented here represent part of the Canadian contribution to a cooperative study sponsored by the International Institute for Applied System Analysis (IIASA) (Parry, Carter, and Konijn 1984). Details of the entire Canadian study are presented in Williams et al. (1986).

The effects of climate change on spring wheat dry matter yield and production are examined using a simple crop growth model developed by Stewart (1981). Climatic change postulated for a doubling of atmospheric CO_2 concentration is analyzed using temperature and precipitation data derived by the general circulation model developed by Hansen et al. (1983) at the Goddard Institute for Space Studies (GISS). The effects of climatic change are discussed in relation to the current "normal" climate, where "normal" is defined as the average climate for the 1951-80 period. Dry matter yields derived for the 1951-80 normal period are used as a reference for establishing the change in production.

METHODOLOGY

Yield and Phenological Models

The procedures used to estimate spring wheat phenological dates and yields are briefly described here. A detailed discussion of the yield model is provided by Stewart (1981) while Robertson (1968) and Williams (1975a) provide more detailed discussion of the phenological model. Calculation of spring wheat yields is based on the methodology developed by the FAO (1978) and uses tabulated results from the de Witt (1965) photosynthesis model to compute "constraint-free" yields. Yield estimates assume a sigmoidal cumulative growth curve with development incremented up to the number of days required for the crop to mature. Net dry matter biomass production (B_n) is calculated as a function of the gross biomass production (B_{gm}) capacity of the crop, determined by its photosynthetic response to temperature and radiation, a maintenance respiration coefficient (C_T), calculated using a method described by McCree (1974), and the number of days required to reach maturity (N). This relationship is expressed as:

$$B_n = 0.36B_{gm}/(1/N + 0.25\ C_T) \qquad \text{Equation 1}$$

To estimate N the biometeorological time scale model developed by Robertson (1968) is used. Robertson's model basically describes the phenological development of "Marquis" spring wheat as a function of temperature and photoperiod in the form:

$$\sum_{i=S_1}^{S_2} [(a_1\ (L_i-a_o) + a_2\ (L_i-a_o)^2)(b_1(Tmax_i-b_o) + b_2(Tmax_i - b_o)^2 + b_3(Tmin_i-b_o) + b_4(Tmin_i-b_o)^2)] = 1 \qquad \text{Equation 2}$$

where L_i is the photoperiod (duration of daylight in hours) on day i, $Tmax_i$ is the maximum air temperature on day i, $Tmin_i$ is the minimum air temperature on day i, S_1 is the date of a phenological stage in the development of wheat toward maturity and S_2 is the next stage, and a_0 to a_2 and b_1 to b_4 are coefficients.

Five phenological phases are considered in the model: planting to emergence, emergence to jointing, jointing to heading, heading to soft dough, and soft dough to ripe. For each stage a different set of a and b coefficients is used.

The date the crop ripens or matures is derived by continuing the summation from the planting date through all five phases. N is then derived as: IEND - ISTART + 1, where ISTART and IEND are the Julian dates that the crop is planted and matures, respectively.

The beginning of the growing season length (GSL) or planting date is calculated as the date the smoothed mean minimum air temperature first exceeds 5°C in the spring. This represents, with a 50% probability, the average date for the last spring and first autumn "killing frosts" (-2.2°C) when using averaged 30-year climatic norms data (Sly and Coligado 1974). In determining this date the monthly temperature data are first converted to daily values using the Brooks (1943) sine-curve technique. The earliest planting date is then derived by computer interpolation of the first day the minimum air temperature reaches 5°C. Similar criteria are used to determine the end of the growing season in the autumn. If an estimated fall frost occurs before the crop reaches a maturity level of 4.8 the crop is assumed killed and the yield component is set equal to zero.

Crop dry matter yield (B_y) is then derived as:

$$B_y = B_n \times HI, \qquad \text{Equation 3}$$

where: HI is the harvest index, defined as that fraction of the net biomass production that is economically useful, i.e., the grain component.

In this study the work of Major and Hamman (1981) at Lethbridge, Alberta, for Neepawa wheat is used to calculate harvest index values. Using their data it was found that the harvest index was inversely related to moisture availability. That is, if moisture is limited, a higher percentage of the crop biomass is converted into yield than if moisture is not limited. This relationship is expressed by using the ratio of actual evapotranspiration to potential evapotranspiration (AE/PE). If the value of AE/PE is greater than 0.75, the value of HI is set equal to 0.35. As AE/PE decreases below 0.75 the value of HI is increased linearly to a maximum value of 0.52. This value is reached when AE/PE has declined to approximately 0.36. In the situation where a frost occurs before the crop reaches a maturity value greater than 4.8 but less than 5.0, HI is extrapolated linearly from 0.0 to 0.35, respectively.

In this study PE is calculated using the Penman (1948) method and AE is derived using a combination soil moisture budgeting/split canopy evapotranspiration model. The former involves using the techniques described by Baier, Dyer, and Sharp (1979) and the latter the work of Ritchie (1972). Details of the procedures used to calculate both AE and PE are provided by Stewart (1981).

Values of B_y computed by equation (3) are constraint-free or genetic potential yields and neglect the effects of yield-reducing factors such as moisture stress; weeds, pests, and diseases; climatic effects on yield components, yield formation, or quality of produce; and field workability.

For the purposes of this study, values of B_y were corrected by a moisture stress yield-reducing factor (MSF) to give values of estimated dry matter yield (B_{ye}), in the form:

$$B_{ye} = B_y \times MSF \qquad \text{Equation 4}$$

All other yield-reducing factors are assumed negligible.

Moisture stress is derived using an expression relating the relative yield decreases to the relative evapotranspiration deficit in the form:

$$MSF = (1 - k_y(1 - AE/PE)) \qquad \text{Equation 5}$$

where k_y is an empirically derived coefficient for crop-yield response to moisture deficit. For spring wheat, the value of k_y is set to 1.15 based on the work of Doorenbos and Kassam (1979).

The procedures for estimating dry-matter yields presented above are designed to evaluate the long-term crop production capability or potential under optimum management conditions on a continental scale from standard climatic information. The input data required include long-term monthly averages of temperature, precipitation, incoming global solar radiation, windspeed, and vapor pressure. These data are normally available from observation networks or, alternatively, can be derived using simple empirical equations.

Climatic Data Input

The monthly climatic data used in the yield calculation are based on the 30-year average 1951-80 Canada normals (Atmospheric Environment Service, 1982) station data. These data, converted by LeDrew et al. (1983) to a 100 km x 100 km equal area grid system covering the land mass area of Canada, were converted to cover the Saskatchewan crop districts, following the procedure described by Stewart (1981). The agricultural region of Saskatchewan is subdivided into twenty administrative areas, or crop districts, for which crop yield data are published annually by the provincial government. The locations of the centroid and reference number for each crop district are given in Figures 1 to 7.

Daily information for all climatic parameters except precipitation were generated from the monthly data using the sine-curve extrapolation technique of Brooks (1943) similar to that described by Williams (1969, 1975a, 1975b), Williams, McKenzie, and Sheppard (1980) and Dumanski and Stewart (1981). Precipitation data were converted to weekly values and then adjusted so that precipitation is received over a three-day period as follows: 60% the first day, 30% the second, 10% the third, and 0% for the remaining four days. Daily information was used in simulating the crop-water balance.

Model Validation

The methodology used in this study was designed to evaluate long-term crop yields under optimum management conditions. As such, there are no long-term experimental results available for comparison in Canada. However, there are short-term experiments available that can be used. Model estimates were compared to experimental work undertaken by Major and Hamman (1981) at Lethbridge, Alberta, and by Onofrei (1984) at six locations in Manitoba.

To compare model estimates with observations at the Alberta and Manitoba sites climatic data including the mean (Tmean), maximum (Tmax), and minimum (Tmin) air temperatures; precipitation totals; and data on soil moisture, observed for each year were obtained. For the Alberta site only, monthly observations were available, while for the Manitoba sites daily data were obtained. Results of the comparison of estimated yields to observed values are given in Table 1. Results show that the model is within 15% of reported values.

Table 1. Comparison of Model Estimates to Observed Experimental Yields in Alberta and Manitoba

Year	Location	No. of Sites	Dry Matter Yield (kg/ha)		Model/ Observed
			Model	Observed	
1976	Alberta[a]	1	3495	3098	1.13
1977	Alberta[a]	1	2454	2623	0.94
1982	Manitoba[b]	6	3547±659	3967±440	0.98
1983	Manitoba[b]	6	2666±607	3098±763	0.86

[a] Data from Major and Hamman (1981) at Lethbridge, Alberta, for Neepawa Wheat.

[b] Data from Onofrei (1984, personal communication) for six sites in Manitoba (Beausejour, Winnipeg, Woodmore, Mariapolis, Bagot and Teulons) for Glenlea Wheat.

These results are remarkably good considering that the model was not designed for use with data for individual years, but rather, for applications employing monthly data averaged over several years. The equations used to compute crop biomass and yield employ averaged growing season information, as opposed to the actual day-to-day values that would be used in a model designed for real-time application. For this reason the model does not simulate plant growth and photosynthetic activity on a daily basis as would be the case with sophisticated models, nor was it intended to do so. It was designed instead to simulate what happens to the crop biomass productivity for averaged growing season conditions. As a consequence, many environmental factors affecting crop growth and productivity are unaccounted for in the model framework. Nevertheless, it is a physically based model using the broad principles of biomass production, and the needed data for large area application are readily available.

It is also emphasized that the comparison outlined in Table 1 involves experimental yields that represent the potential or maximum yields that can be obtained under optimum management practices. They do not represent the yields obtainable under current commercial conditions which are considerably less than the potential. For example, reported commercial yields were 59% and 60% of the values given in Table 1 for experimental wheat yields for 1982 and 1983, respectively, in Manitoba. Similarly, in Alberta the ratio was 76% and 70%, respectively, for 1976 and 1977. For this reason, all scenario yield estimates are expressed in terms of percent of normal, where normal represents the model estimate derived using the climatic data averaged for the 1951-80 period. It is assumed that the effects on yields of variations in climatic conditions are the same for both commercial and experimental spring wheat production. It is also assumed that existing technology and climatic tolerances of the existing spring wheat cultivars grown in Saskatchewan remain unchanged.

Modification of Input Data to Simulate Climate Change

Climatic change is simulated in this study using the GISS 2 x CO_2 general circulation modeling results of Hansen et al. (1983). Theoretically derived monthly mean temperature and precipitation data computed for a doubling of CO_2 by the GISS model were obtained from Bach (1986). Temperature and precipitation data for the Saskatchewan study area were obtained in the form of a 4° latitudinal by 5° longitudinal grid square framework for a control case representing the current climate and for a 2 x CO_2 climate. For the purposes of this study the differences in temperature between the control (1 x CO_2) and 2 x CO_2 climates were used to adjust the temperature data from normal, while the ratio of the 2 x CO_2 climate to control was used to adjust the monthly precipitation totals from normal. For simplicity, this scenario is referred to as GISS1. Three additional scenarios using various combinations of the GISS1 data will also be discussed in the following sections. These scenarios, referred to as GISS2, GISS3, and GISS4, will be defined later.

In all, 9 GISS grid points cover the Saskatchewan study area. These were at 50°, 54°, and 58°N latitude and 100°, 105°, and 110°W longitude. Temperature and precipitation data for these points were plotted and mean adjustments for each crop district were interpolated from the mapped results. Monthly temperature and precipitation changes averaged for the entire Saskatchewan agricultural area are listed in Table 2. To estimate maturity and biomass parameters in the model, values for Tmax and Tmin are required. Since only GISS Tmean data were available, it was assumed that any change in Tmean affected Tmax and Tmin equally (i.e., if Tmean increases by 1°C, then both Tmax and Tmin are assumed to increase by 1°C).

Climatic change for all scenarios is simulated in the yield model by adjusting the 1951-80 monthly norms data with the corresponding temperature and precipitation data obtained for each scenario. All other climatic data input required by the yield model are fixed at the 1951-80 normal level.

Table 2. Monthly Temperature and Precipitation Adjustments Used in the Yield Model to Represent the GISS 2 x CO_2 Scenario

Month	Temperature[a]	Precipitation[b]
January	6.1	1.29
Febuary	5.6	1.34
March	4.8	1.24
April	4.1	1.17
May	3.7	1.15
June	3.3	1.15
July	3.3	1.13
August	3.7	1.05
September	4.6	0.99
October	5.3	1.12
November	5.9	1.26
December	6.3	1.30
AVERAGE	4.7°C	1.15

[a] All 1951-80 monthly temperature data were adjusted by addition of these values. Values represent the difference between GISS 1 x CO_2 and GISS 2 x CO_2 estimates.

[b] All 1951-80 monthly precipitation totals were adjusted by multiplication by these values. Factors represent the ratio of GISS 2 x CO_2 to GISS 1 x CO_2 model estimates of precipitation.

CLIMATIC WARMING--WHAT DOES IT MEAN?

If Saskatchewan were to undergo the projected climatic change suggested by the GISS model, how would the new climate compare with the present climate? The following discussion attempts to outline some of the changes we might expect.

Table 3 outlines the computed growing season start and end dates for the 1951-80 norms and the GISS scenario. As shown, the growing season start (GSS) varies from May 17 to May 27 and the growing season end (GSE) occurs between September 10 to September 15. Average growing season climatic conditions for the 1951-80 normals period in Saskatchewan are illustrated in Figures 1a to 4a. Figure 1a outlines the GSL available for crop growth; Figure 2a, the thermal resources available during the growing season, expressed in degree days above 5°C (DD5); Figure 3a, the available moisture in terms of precipitation occurring during this growing period; and Figure 4a, the evaporative demand or ratio of precipitation to potential evapotranspiration (precipitation/PE) that existing crops are adapted to. These figures basically define the growing season as being relatively short, warm, and dry. The average GSL varies from 100 to 120 days, generally decreasing in a south to north direction. The exception to this pattern is in the southwest corner of the study area where the higher elevation of the terrain, particularly in the Cypress Hills, results in the GSL being of similar duration to that of the more northerly agricultural area of the province. DD5, as presented in Figure 2a, follows the pattern of the growing season length, with the greatest amount of heat in the central part of the study area (1400 DD5) and the least in the north (1100) and southwest corners (1200). Also, as shown in Figure 3a, the southwest corner of the study area is the driest, with total growing season precipitation averaging slightly less than 180 mm. Values increase to slightly more than 240 mm in the northestern part of the study area. Figure 4a highlights the dryness of the region indicating that the precipitation it receives is enough to supply only 35% of the evaporative demand in the dry southwest, slightly more than 50% in the east, and 60% in the north.

Given that the existing growing season climate in Saskatchewan is short, warm, and dry at present, what sort of average change might we expect given the warming projected by the GISS model? Table 2 outlines the monthly temperature and precipitation adjustments for Saskatchewan. As shown, monthly temperatures vary from an increase of 3.3°C in June and July to 6.3°C in December and January. Altogether, the warming suggested by the GISS model would increase the annual temperature in Saskatchewan by about 4.7°C. Furthermore, precipitation is also expected to increase. Monthly increases ranging from 5% to 15% during the summer, to a slight decrease in September of 1%, to an increase in the winter of slightly more than 30% are projected. In terms of annual precipitation totals, levels are projected to increase from 14% to 18% above the current level. The projected May to August total which makes up 51% to 57% of the current annual value will not change (i.e., 50% to 55%).

Table 3. Estimated Changes in Growing Season Start and End Dates (Julian) and Growing Season Length (Days) by Crop District in Saskatchewan for the 1951-80 Normal Period and GISS 2 x CO_2 Temperature Increase

Crop District	Growing Season Start 1951-80	Growing Season Start GISS	Growing Season End 1951-80	Growing Season End GISS	Growing Season Length 1951-80	Growing Season Length GISS
1a	140	118	256	285	117	168
1b	138	117	258	288	121	172
2a	140	119	256	286	117	168
2b	178	117	258	288	121	172
3an	139	118	258	287	120	170
3as	142	123	254	284	113	162
3bn	139	122	257	283	119	162
3bs	145	125	251	282	107	158
4a	144	126	251	280	108	155
4b	137	124	258	276	122	153
5a	140	128	257	287	118	170
5b	144	126	253	285	110	160
6a	139	118	257	287	119	170
6b	138	117	258	286	121	170
7a	139	120	256	282	118	163
7b	138	118	257	284	120	167
8a	147	129	252	284	106	156
8b	140	124	257	286	118	163
9c	146	128	252	284	107	157
9b	145	127	253	284	105	158
Prov Ave.	141 ±3	122 ±4	255 ±3	284 ±3	116 ±5	164 ±6

141 = May 20   255 = September 12

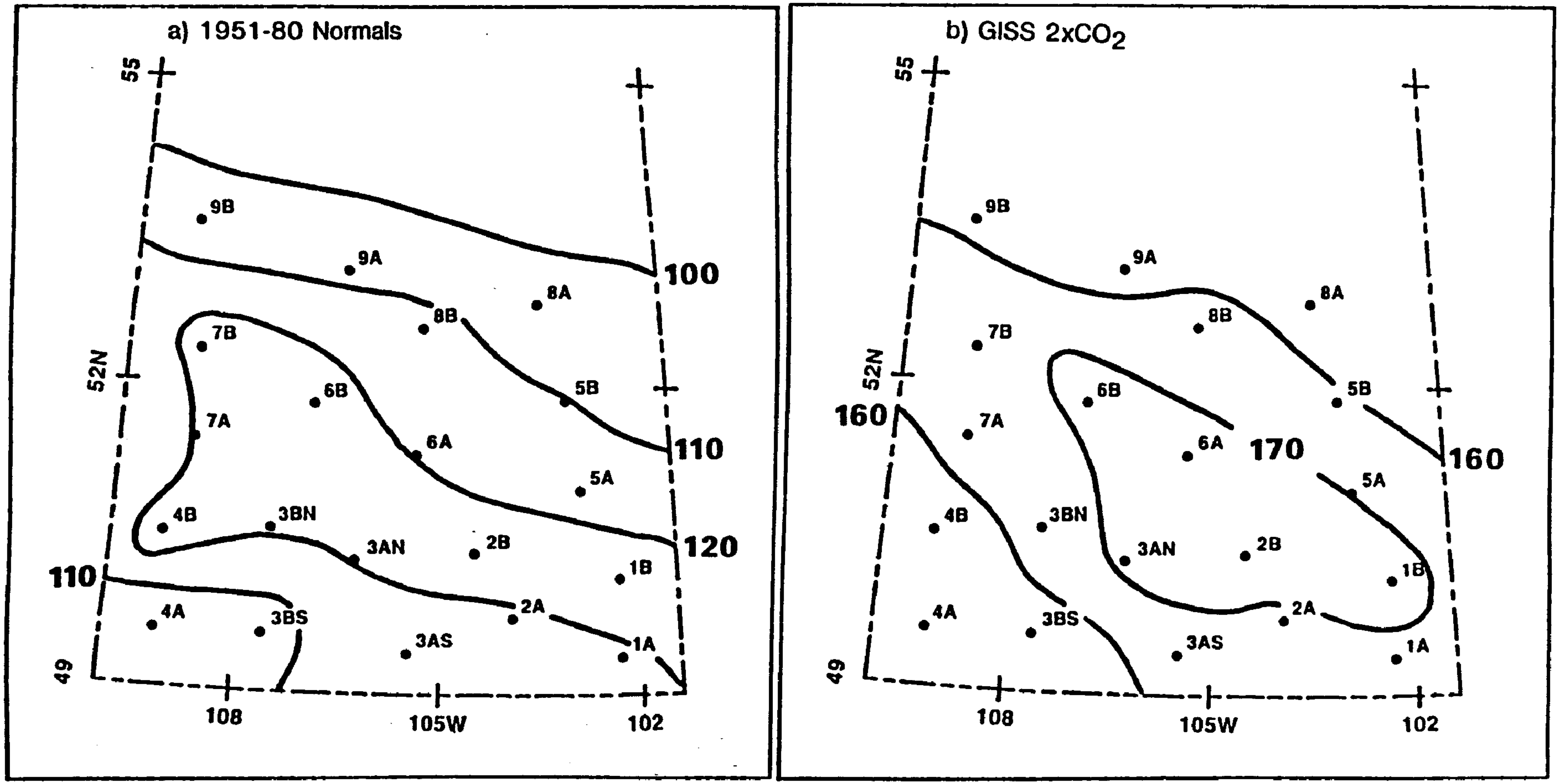

Figure 1. Variation in the Growing Season Length (Days) in Saskatchewan Derived for the 1951-80 Normals Period and GISS 2 x CO_2 Scenario.

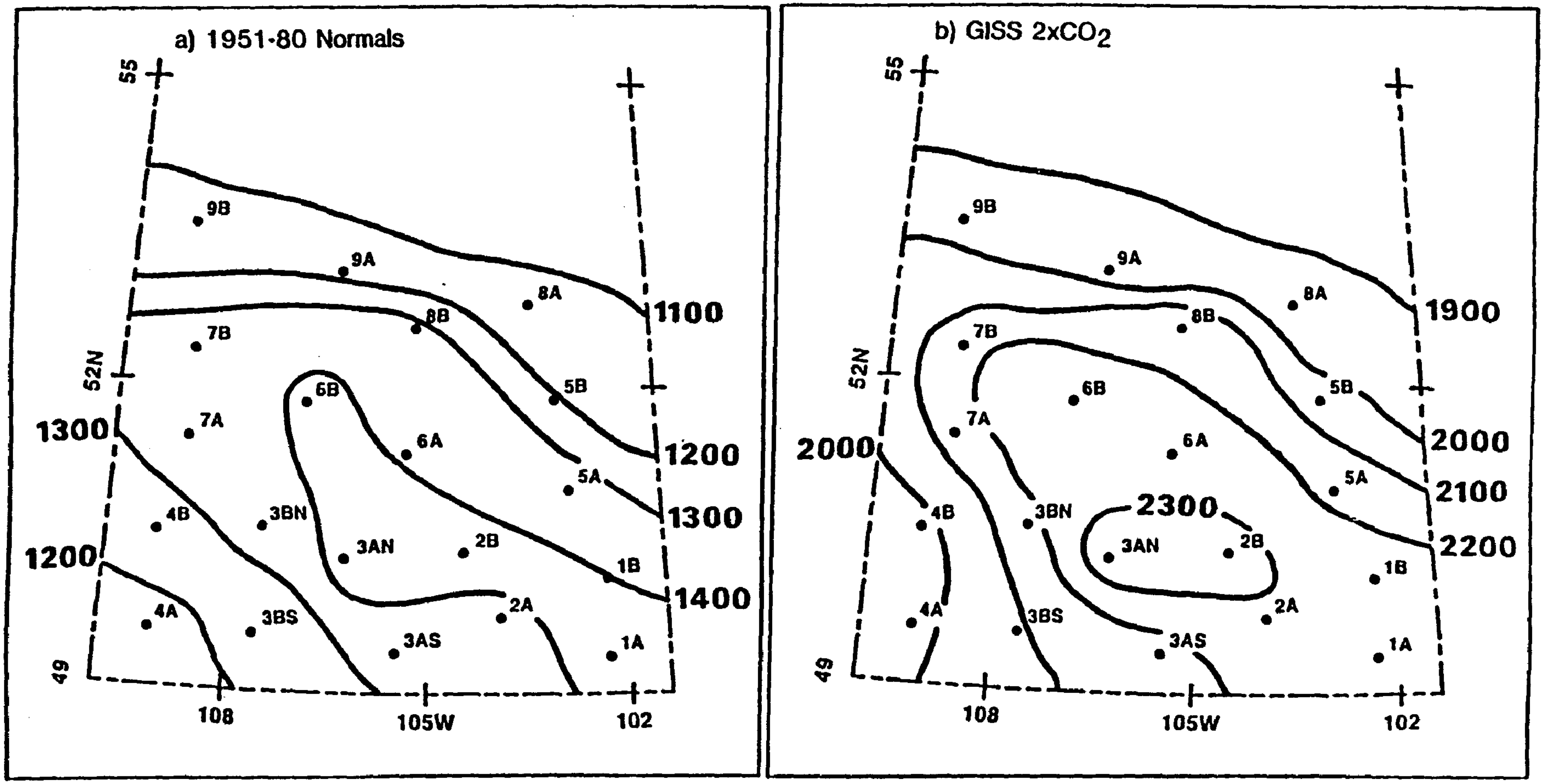

Figure 2. Variation in Growing Season Degree Day Totals Greater Than 5°C in Saskatchewan Derived for the 1951-80 Normal Period and GISS 2 x CO_2 Scenario

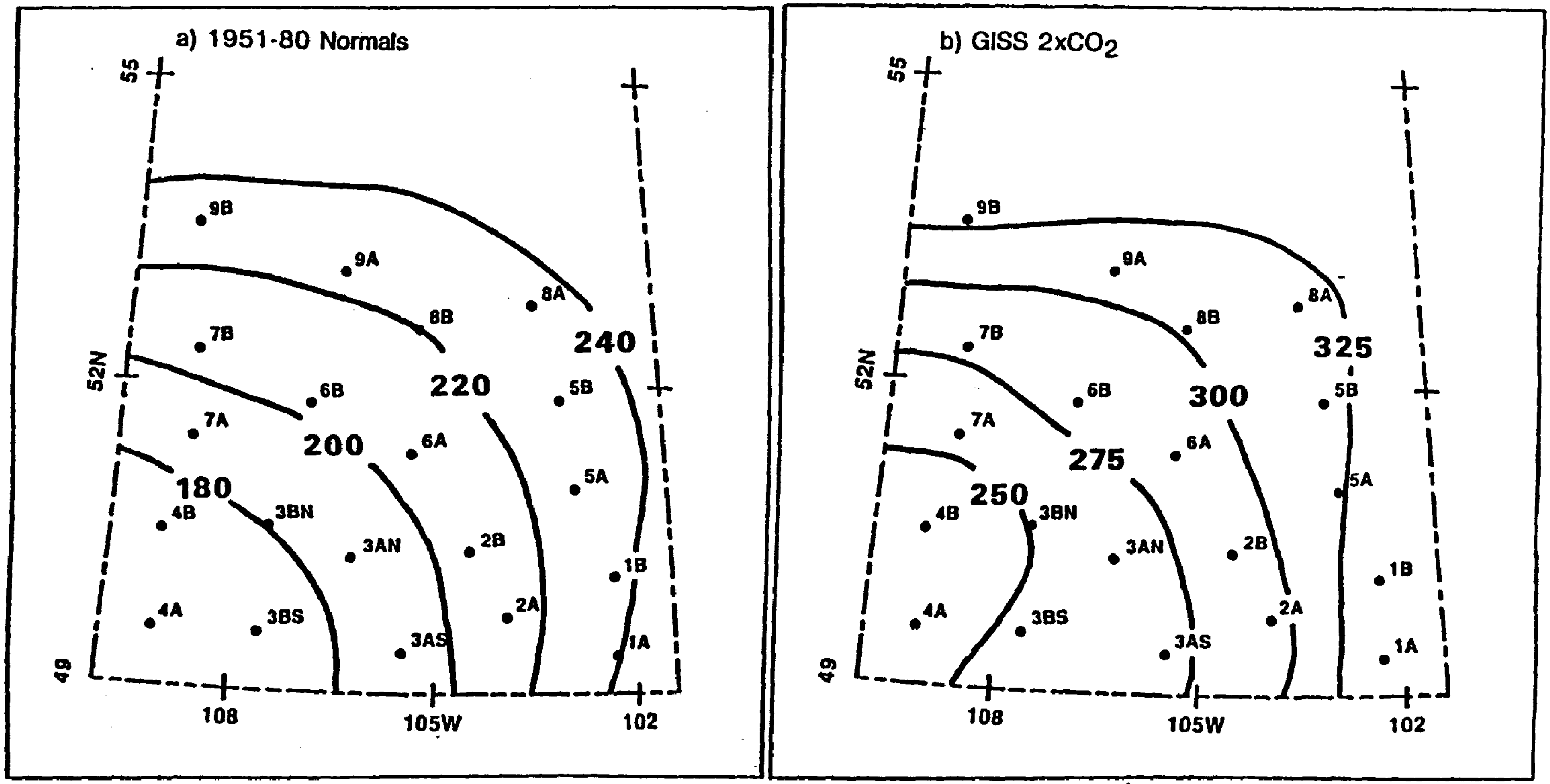

Figure 3. Variation in Growing Season Precipitation Totals (mm) in Saskatchewan Derived for the 1951-80 Normals and GISS 2 x CO_2 Scenario

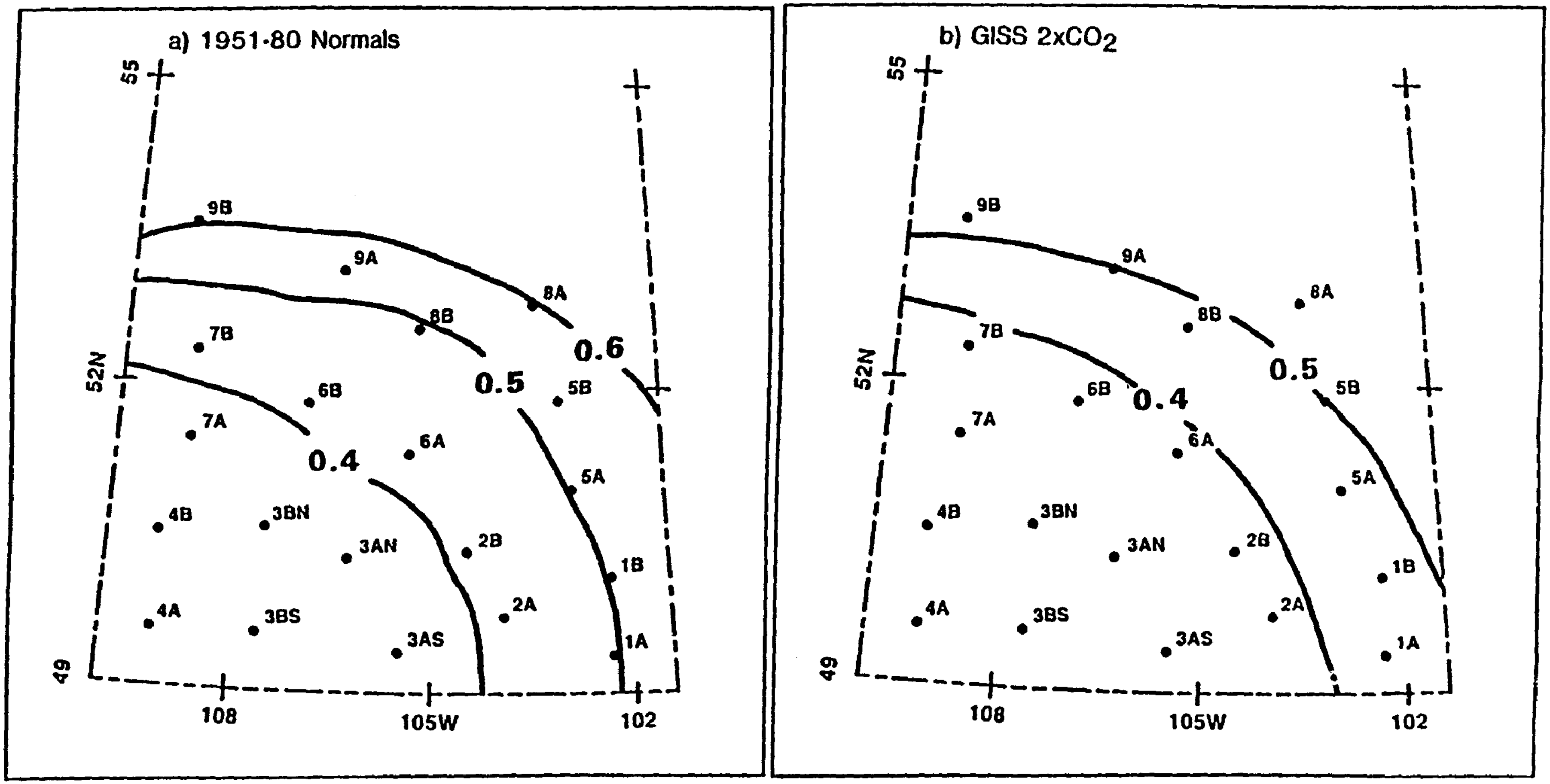

Figure 4. Variation in the Growing Season Ratio of Precipitation to Potential Evapotranspiration (Pipe) Derived for the 1951-80 Normals and GISS 2 x CO_2 Scenario

Figures 1b, 2b, 3b, and 4b outline the change in GSL, DD5, and precipitation received during the growing period and the precipitation/PE ratio. Comparing Figures 1a and 1b, 2a and 2b, and 3a and 3b reveals little change from the current isoline patterns. For example, the length of the growing season will increase by an average of 48 days or by 40% to 50%; the increase will be distributed relatively uniformly across the province. The increase in GSL will affect both the GSS and GSE. The GSS will be advanced an average of 19 days and will range from April 27 in the southeast to May 9 in the north. Similarly, the GSE will be extended by an average of 29 days in the fall from October 7 in the southwest, October 11 in the north, and October 15 in the southeast. In conjunction with the increase in GSL, the higher temperatures will also augment the total available heat by about 800 DD5 or by 60% to 70%. In both cases, the largest changes will take place in the northern half and the southwestern corner of the agricultural area; the least impact is in the central and southeastern parts. In essence, the effect of the projected GISS warming on the climate of Saskatchewan would be tantamount to a shift of the climate in Nebraska north to Saskatchewan. Given a climate change of this magnitude what sort of impact might we expect to see on spring wheat production in the prairies? The following sections outline the impact on maturity, yield, and production potential.

RESULTS

In analyzing the GISS scenario, an attempt is made to assess the likely effects on spring wheat yields and production resulting from the implied shifts in long-term average climate. It is recognized, however, that spring wheat is not the only crop that would be affected by these perturbations and shifts. Assessing the impact on all crops, however, is beyond the scope of this report.

In discussing the impacts of CO_2-induced climatic change on spring wheat yields the following sections outline the effect of the temperature changes on the ability of spring wheat to mature, the effect of temperatures and precipitation on yield, and subsequently, on provincial crop production.

Impact on Spring Wheat Maturity

As shown in Table 4, the average time required for spring wheat to mature, as determined by the Robertson (1968) biometeorological time scale for 1951-80, ranges from 86 to 98 days with the lower values observed in the southeast and central crop districts (Figure 5a). Comparing these maturity requirements with the available DD5 (Figure 2) shows the close correlation of the length of time required to reach maturity and the total heat available. Comparing the DD5 of spring wheat from planting to ripening indicates that spring wheat requires from 1000 to 1100 DD5 in Saskatchewan. These results, while ignoring the effect of daylength, indicate that the amount of heat required for wheat to mature is basically the same throughout the agricultural area in Saskatchewan. The key factor affecting wheat development is the rate of heat accumulation, and as can be seen from examining Figures 2a and 4a, the areas with the longest maturation time requirement correspond to the coolest areas. Conversely, the warmer the temperature, the faster the spring wheat matures.

Table 4. Average Temperature (°C) Difference from the 1951-80 Normal Period from Planting to Maturation for Spring Wheat in Saskatchewan for the GISS 2 x CO_2 Scenario

Crop District	1951-80 Normal Maturation Time (Days)	1951-80 Normal Mean Temp (°C)	GISS Maturation Time (Days)	GISS Mean Temp (°C)
1a	88	17.1	84	1.0
1b	87	17.1	83	1.1
2a	86	17.2	82	1.3
2b	86	17.3	82	1.3
3an	87	17.5	82	0.9
3as	88	17.0	82	1.4
3bn	89	16.9	82	1.5
3bs	92	16.7	82	1.5
4a	96	16.3	84	1.8
4b	98	15.9	84	1.7
5a	89	16.8	84	1.0
5b	92	16.2	81	1.8
6a	87	17.1	83	1.1
6b	87	17.1	82	1.0
7a	88	16.9	82	1.3
7b	89	16.7	82	1.2
8a	93	16.0	79	1.9
8b	87	16.7	80	1.5
9a	95	15.8	82	2.1
9b	94	15.7	82	2.1

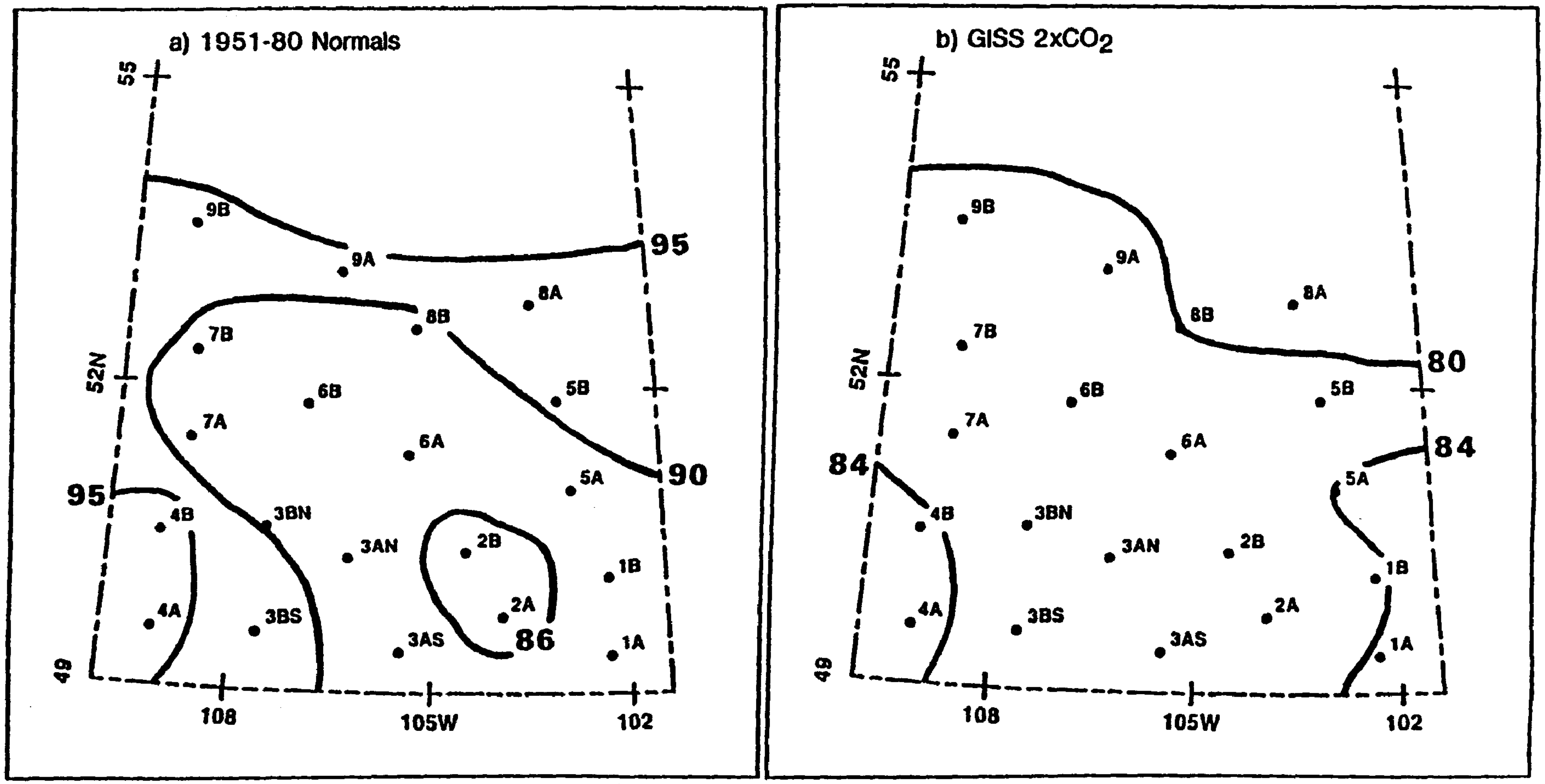

Figure 5. Variation in Average Spring Wheat Maturation Time (Days) in Saskatchewan for the 1951-80 Normals and GISS 2 x CO_2 Scenario

Derived maturation requirements for the GISS1 scenario are shown in Figure 5b; the difference from the norm is given in Table 4. The primary impact of the large-scale warming associated with GISS is to reduce maturation time for current spring wheat varieties to the 79- to 84-day range, a decrease of 4 to 14 days. However, unlike the current maturation requirement where the longest requirement is in the northern part and southwestern corner of the agricultural area, with the GISS warming this pattern tends to be reversed. That is, the northern region has the shortest requirement, 79 to 80 days, as opposed to 82 to 84 days in the south and central parts. A further impact of the warming suggested by GISS is that the difference in maturation time would tend to disappear as the region becomes much more homogeneous (i.e., currently there is a 12-day range in maturation from 86 to 98 days; for GISS the range decreases to 5 days, 79 to 84 days). Both effects, in addition to the temperature increase, are augmented by the advance in the planting date of two to three weeks and the coincident greater increases in northern districts' daylengths (the biometeorological time scale considers both temperature and daylength in determining crop development).

In Table 4 the average temperature experienced by the crop from planting to maturity is given for the 1951-80 norm and GISS1 scenario. As shown, at present the temperature range in Saskatchewan is about 1.5°C from the north and southwest to the south central part (i.e., 16°-17.5°C). Data presented in Table 4 for the GISS1 scenario reveal two interesting features. First, the range in mean temperatures over the course of spring wheat maturation throughout Saskatchewan is reduced, tending to make the agricultural area more homogeneous (i.e., range in temperature with GISS1 condition is about 0.8°C). Second, and most interesting, the effective temperature increase that the wheat crop is exposed to ranges from 1.0°-2.1°C, not the average 3.3°C increase shown in Table 2. In this instance the effective temperature increase is greatest in the north and southwest parts of Saskatchewan and the least in the southeast and central areas. The greatest temperature increases are coincident with the areas with the largest reduction in maturation time. The reason the full temperature increase (i.e., 3.3°C) is not experienced by the crop is the advance in the growing season planting date by about three weeks.

Impact of GISS Temperature and Precipitation Changes on Yield

Figure 6a shows the impact on spring wheat yields in relation to the norm for the projected GISS changes in temperature and precipitation (GISS1). Results suggest that the overall effect of warming would be a general decrease in yields. The southern area would be less affected than the north with yields remaining within 20% of current levels, whereas in the north, yield reductions of 25% to 35% could be expected.

To estimate the overall impact on total spring wheat production, the average extent (hectarage) of crop districts in Saskatchewan for the period 1961-79 were used (Table 5). The production potential for each crop district was calculated by multiplying the derived yield by the average extent. The total provincial production potential was then derived by summing the production values for all crop districts. The results for all scenarios in relation to the 1951-80 computed total are given in Table 6.

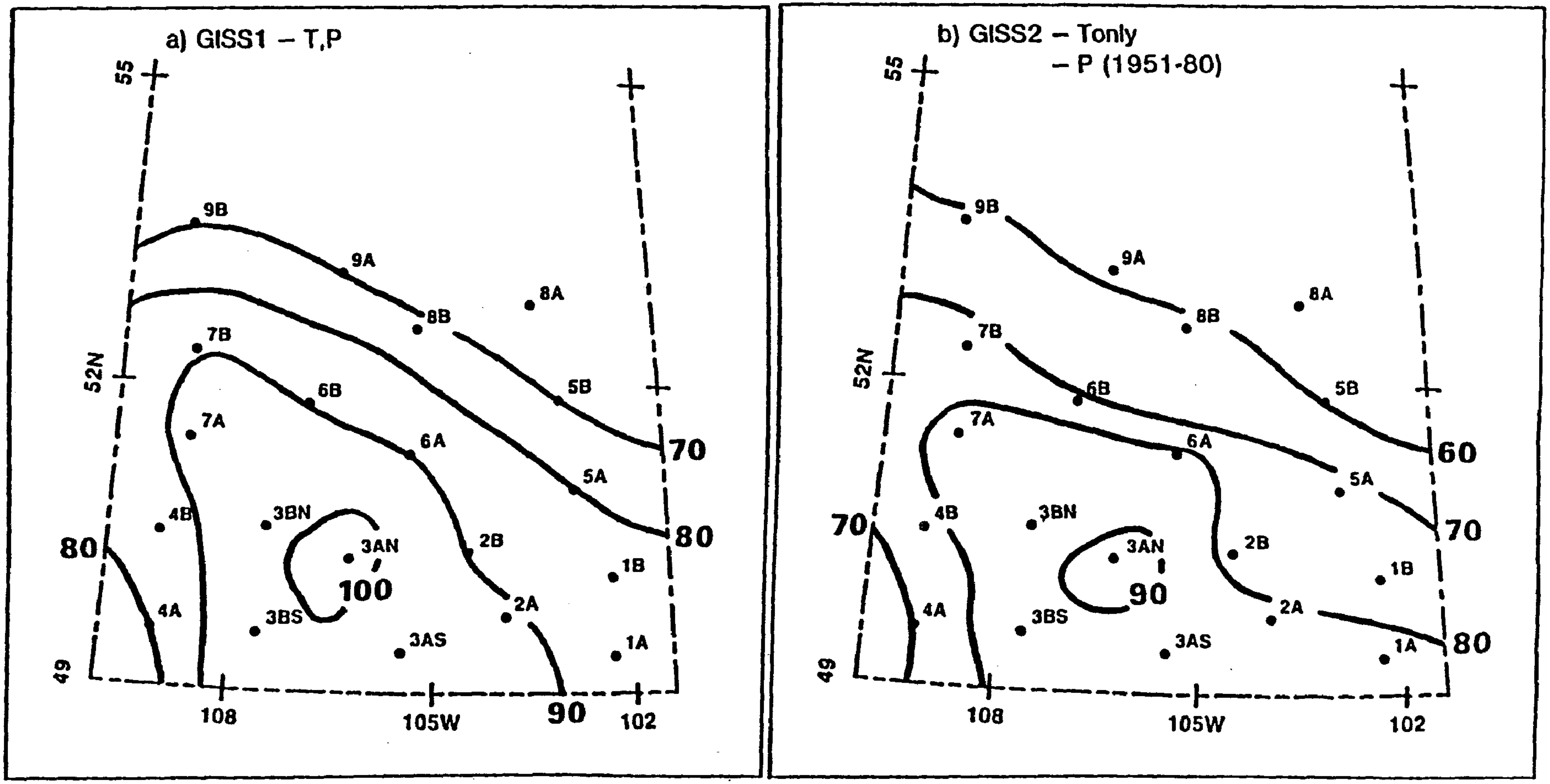

Figure 6. Variation in Spring Wheat Yields of the 1951-80 Normal for the GISS1 and GISS2 Climate Scenarios

Table 5. Saskatchewan Crop District Extent (ha, thousands), Yield (kg/ha), and Production (tons, thousands) of Spring Wheat Average for 1961-79

Crop District	Extent (1000 ha)	Yield (kg/ha)	Production (1000 tons)
1A	306.06	1555	476.15
1B	217.03	1679	364.41
2A	308.34	1533	472.72
2B	421.33	1719	724.40
3AS	460.96	1480	682.16
3AN	246.74	1458	359.62
3BS	332.32	1383	459.65
3BN	456.52	1480	675.58
4A	162.57	1232	200.23
4B	254.29	1443	367.00
5A	419.41	1695	710.93
5B	375.04	1760	660.22
6A	577.49	1582	913.33
6B	436.30	1526	665.74
7A	419.39	1678	703.56
7B	311.16	1700	528.91
8A	190.30	1789	340.44
8B	280.21	1768	495.29
9A	283.75	1655	469.59
9B	191.20	1713	327.50
TOTAL	6,650.41	1593	10,597.33

Table 6. Change in Saskatchewan Spring Wheat Production from the 1951-80 Normals for the GISS 2 x CO_2 Scenario

	1951-80	GISS1	GISS2	GISS3	GISS4
% OF 1951-80 Normal	100	84.3	74.3	94.4	86.5

GISS1 - Temperature and precipitation

GISS2 - Temperature only, precipitation held constant at 1951-80 level

GISS3 - Temperature, precipitation and 15% increase in photosynthetic capacity

GISS4 - Temperature and 15% increase in photosynthetic capacity - precipitation held constant at 1951-80 level

Table 7. Differences in Temperature (T) and Precipitation (%P) from the 1951-80 Normal Period for 1933-37, 1961 and GISS 2 x CO_2 Scenario for a Cross Section of the Saskatchewan Study Area Averaged for the Four Months May, June, July, and August

Crop District	1951-80 T(°C)	1951-80 P(mm)	1933-37 T	1933-37 %P	1961 T	1961 %P	GISS 2 x CO_2 T	GISS 2 x CO_2 %P
1A	17.46	248.7	-1.3	0	+0.3	38	+3.4	115
3BS	15.29	195.5	+1.2	88	+2.5	50	+3.4	115
4B	14.72	176.5	+2.3	78	+3.5	57	+3.4	115
7A	15.83	195.8	+1.0	55	+1.8	45	+3.4	115
7B	15.72	210.4	+0.1	75	+1.3	64	+3.4	115
9B	14.45	247.8	+0.3	70	+1.7	61	+3.4	115

GISS1 results suggest that the yield reductions in Saskatchewan would occur in spite of the projected precipitation increase of approximately 15% above current levels. This precipitation increase is more than offset by the adverse effects associated with the higher temperatures.

From a historical point of view the projected GISS warming presents an interesting contradiction, since historically, when temperatures have been above normal, precipitation has had a tendency to be below normal. Table 7 illustrates this point clearly, using data for the period 1933-37 and 1961 as examples. Both represent years when major drought was experienced in the Canadian prairies. Results also show that, historically, temperature deviations have tended to vary considerably throughout the region.

The GISS data on the other hand indicate a relatively uniform change in both temperature and precipitation. Because of this, it is of particular interest to have some indication of the contribution of the precipitation increase projected by the GISS model to the estimated impact on spring wheat yields and production.

This was undertaken by rerunning the yield model with the GISS temperature adjustment only (GISS2); precipitation was held constant at the 1951-80 level. The results (Table 6) indicate that potential production would be reduced overall by 16% for GISS1 and 26% for GISS2. In other words, a further reduction of 10% in spring wheat yields could be anticipated if the climatic warming predicted by GISS occurred but precipitation remained at the 1951-80 level. The spatial pattern for GISS2 (Figure 6) is quite similar to that for GISS1 (Figure 6a), which reflects the fact that the additional 10% reduction resulting from ignoring the GISS precipitation increases is spread uniformly throughout Saskatchewan.

The above results further suggest that precipitation will have to increase significantly above the 15% level projected by the GISS model to maintain production at current levels. If the precipitation stays the same or decreases, given the warming suggested by GISS, spring wheat production would be reduced sharply from current levels.

Impact of Increased CO_2 on Photosynthesis

In the above discussion the effect of temperature and precipitation on spring wheat production has been considered while the direct effects of increased CO_2 on photosynthetic capacity have been ignored. Various studies have suggested a number of possible beneficial effects arising from the increase in CO_2 concentration on plant productivity. Kimball (1983), from the results of a literature review, suggests, for example, that yields would increase by approximately 33% with a doubling of CO_2 concentration. Gifford (1979), Lemon (1983) and Aston (1984) have indicated that improved efficiency in the use of plant moisture would be another direct effect.

In Kimball's review, much of the data reported was obtained from growth chamber experiments which are notorious for oversimplifying the study of environmental factors on plant productivity in comparison to actual field studies. In growth chamber studies, such as those carried out by Gifford (1979) and Sonit, Hellmers, and Strain (1980) to investigate the effect of elevated CO_2 levels on crop growth and yield, light, temperature, and humidity, levels were kept constant in simulating day and night conditions. In controlled studies of this sort, plant stresses are generally minimized to isolate or study the effect of a particular environmental parameter. Consequently, the results often differ considerably from actual field conditions where the diurnal light, temperature, and moisture levels fluctuate considerably from day to day and throughout the course of a crop's growth. For this reason the increase in productivity reported by Kimball (1983) can be viewed as unrealistically high. Reported field experiments for spring wheat support this contention. For example, experiments by Krenzer and Moss (1975) and Havelka, Wittenbach, and Boyle (1984) found that for wheat crops grown under field conditions with elevated CO_2 levels the effect on dry-matter yields was about half the magnitude suggested by Kimball (1983), i.e., 15% for Krenzer and 11% for Havelka. In the former, results were obtained with a doubling of CO_2 concentration, while in the latter, results were obtained with a 4 x CO_2 increase.

In this study the possible direct effects of an increase in CO_2 on increased photosynthesis and moisture use efficiency are considered. Using the results of Krenzer and Moss (1975) and Havelka, Wittenbach, and Boyle (1984) as a basis, photosynthetic capacity of the spring wheat crop was increased by 15% to simulate direct effects on plant growth (GISS3). The results are presented in Figure 7a in combination with the GISS temperature and precipitation increase. The results show that, in spite of the increase in productivity associated with elevated CO_2 levels, provincially, that a 15% increase in photosynthetic capacity would not be enough to overcome the adverse effects of elevated temperatures and moisture stress. Production would still decrease by approximately 6%. Results indicated that an increase in photosynthetic capacity of approximately 20% to 25% would overcome the temperature and moisture effects.

As shown in Figure 7a, the yield pattern is similar to that described for the GISS1 scenario. Overall, the 15% change in photosynthetic capacity increases the provincial dry-matter production potential by about 10% above

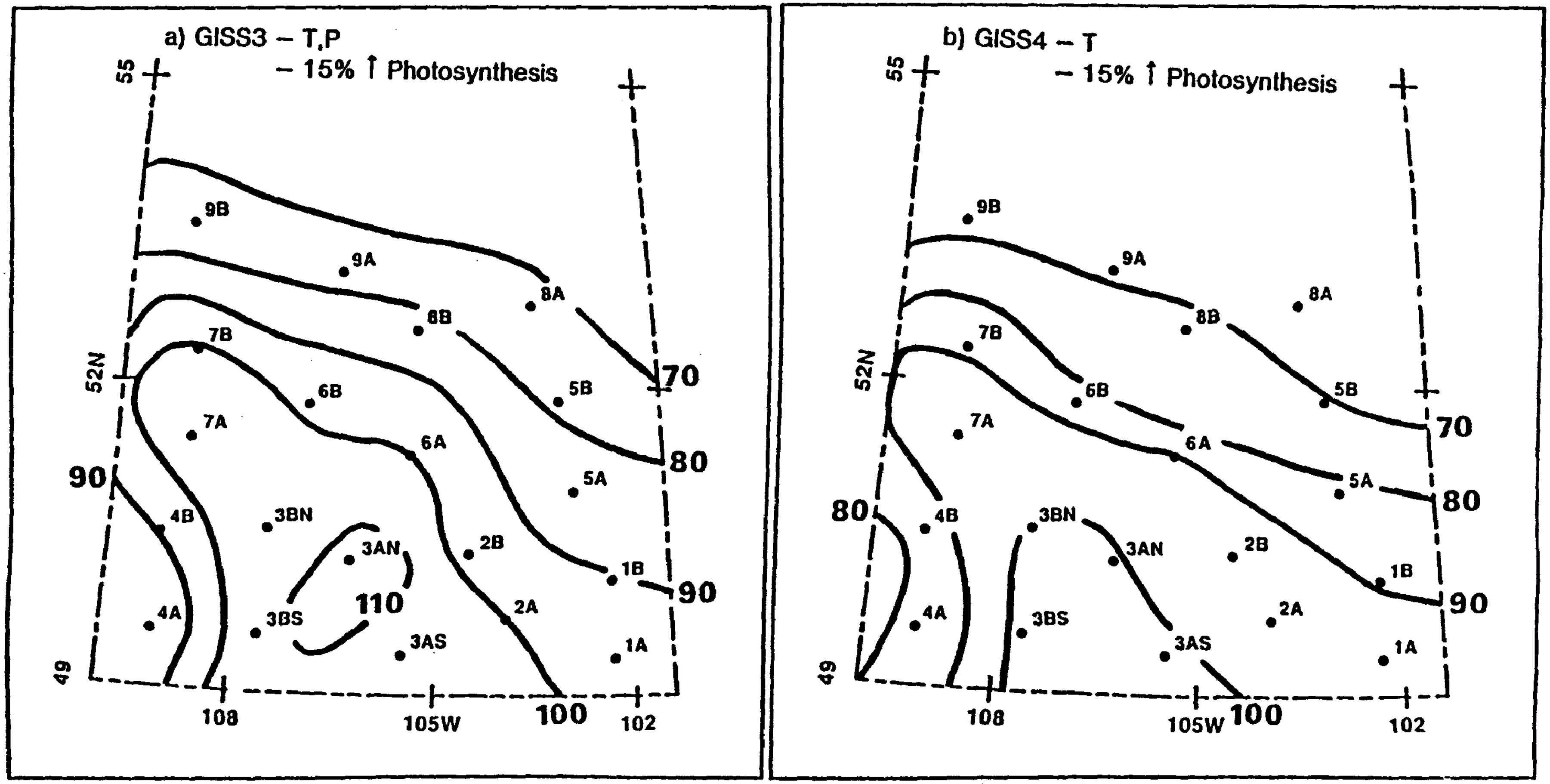

Figure 7. Variation in Spring Wheat Yields (% of Normal) in Saskatchewan for the GISS3 and GISS4 Climate Scenarios

the GISS1 level. Again, yields are more affected in the north with a 20% to 30% decrease while in the south central part of the province yield changes range from a slight decrease (10%) to a slight increase (15%). Assuming the 15% increase in photosynthetic capacity and the GISS temperature increase only, and holding precipitation constant at current levels--GISS4, as shown in Figure 7b--the effect of precipitation is a reduction of about 10% in yields in comparison to GISS3.

The above results show the impact of potential long-term average climate change on spring wheat production in Saskatchewan. In general, the results suggest that the overall impact would decrease spring wheat production by 6% to 26%.

The Effect of Increased Drought

The slight decrease in production, outlined above, can be attributed primarily to an advance in the growing season start (planting date) of about three weeks and associated higher light levels, the latter enhancing crop photosynthetic activity. The GISS model predicts that the region would be only slightly drier. However, the question one might ask is how might a climate change of the sort projected by the GISS model affect drought potential in the region (i.e., the frequency and severity of drought events)? Drought is a critical element of concern today and must be considered in any future climatic change scenarios. The stability of prairie agriculture can be badly shaken if drought frequency and severity increases. The last five years clearly illustrate the impact that drought has had on prairie wheat production and, subsequently, on the economy. Given the projected GISS climate change, what sort of effect might we expect in drought frequency and severity?

Williams et al. (1986) have examined this feature using the GISS model projections. In their study, drought frequency and duration changes were examined using the well-known Palmer Drought Index (Palmer 1965). Using this index, drought is taken as the interval of time, generally on the order of months, during which the actual soil moisture supply at a given place consistently falls short of the climatically expected or climatically appropriate moisture supply (Williams et al. 1986). The severity of drought is a function of both duration and magnitude of the moisture shortfall.

In the Williams et al. (1986) study, various Palmer Drought Index (PDI) values were characterized in terms of the deviation from the 1951-80 normal climate, as follows: greater than +6--severe wet spell, +4 to +6--extremely wet, +2 to +4--wet spell, +2 to -2--near normal, -2 to -4--dry spell, -4 to -6--drought, and less than -6--severe drought. A value of -4 to -6 over a period of several months is generally reflected in lower crop yields and water supply problems while a severe drought (PDI < than -6) has serious economic consequences because of water shortages and potential crop failure.

Results of the PDI analysis in Saskatchewan by Williams et al. (1986) suggest that the GISS warming would lead to a more drought-prone climate, primarily because of increased evapotranspiration associated with the elevated temperatures. The existing variability of dry and wet spells, however, would remain unchanged. Specifically, Williams et al. (1986) suggest that the following might occur:

- The frequency of drought months (below -4) would be increased by a factor of 3 (3% to 9%). If the GISS temperature increase occurred and precipitation remained at current levels, as simulated in the above results, drought month frequencies would increase by a factor of 10.

- Drought duration would be longer and more severe.

- The return period of drought (below -4.0) and severe drought (below -6.0) events would be halved (see Table 8).

The results of Williams' analysis would suggest that the relatively minor long-term yield changes derived from the modeling exercise presented in the sections addressing the impact of temperature and precipitation changes on yield and the effect of increased CO_2 on photosynthesis could be somewhat of an over-simplification. Indications are that fluctuations in yield from year to year could be quite significant with drought years becoming more frequent and more severe. At the same time good years would also occur. Ultimately, in a highly unstable environmental setting such as that projected by the GISS example, the current spring wheat cropping system would most certainly be put to the test in terms of the farmers' ability to cope financially with good and bad years, assuming that price is not the problem (as is the case today).

Shifting Crop Boundaries

In the analysis presented above, the effects on spring wheat production were discussed. No attempt was made to look at changes in crop zonation, that is, the movement of major crop boundaries or replacement of certain types of crops by others as a result of the environmental changes incurred. Recently, Rosenzweig (1984) has assessed the implications of the GISS results for a doubling of CO_2 concentration on North American wheat zonation using the simple environmental criteria listed in Table 9. These criteria describe fairly accurately the current zonation illustrated in Figure 8 for North America.

Defining the growing season as the number of days between the last frost in the spring and the first frost in the fall (0°C) and applying the environmental criteria listed in Table 9 to the GISS data, the wheat zonation map illustrated in Figure 9 was derived. In this analysis, the GISS data were applied over an 8° latitudinal x 10° longitudinal grid system covering the land mass area of North America. As shown, the effect of the GISS climate change would be the expansion of the winter wheat region in the northern United States north into Canada and the extension of the fall-sown spring wheat region northward and eastward. The results in relation to moisture, at least in terms of annual requirements, appear to be generally adequate for wheat production. However, they do not take into account the change in evaporative demand, which would be increased with the elevated temperatures and increased vapor pressure deficits during the growing season.

Rosenzweig's results indicate that the climatic change postulated for GISS would be conducive to the shift of the winter wheat belt in the U.S. into the Canadian prairies. They do not imply, however, that spring wheat production in Canada would be replaced by winter wheat. Due to the very large grid framework (very large area) used, changes in the temperature and precipitation

Table 8. Return Period in Years for Palmer Drought Index Values of < -4.0 (Drought) and < -6.0 (Severe Drought) Derived for Selected Stations in Saskatchewan

	-4.00 (drought)		-6.00 (severe drought)	
STATION	1951-80	GISS	1951-80	GISS
Yorkton	7.0	4.0	19.0	10.0
Kindersley	19.9	5.6	35.0	17.0
Swift Current	8.6	5.3	28.0	15.0
Moose Jaw	8.0	5.0	23.5	13.5
Regina	6.6	4.2	27.0	10.0
Prince Albert	8.5	5.3	24.0	13.5
North Battleford	9.5	5.7	30.0	16.0
Saskatoon	9.5	6.0	31.0	17.5
Hudson Bay	10.0	4.4	34.0	13.5
Broadview	6.5	4.1	15.0	8.5
Estevan	6.8	4.4	19.0	11.2

Source: Table 2.5, Williams et al. (1986).

Table 9. Wheat Environmental Requirements Used in Classification of Wheat-Growing Regions of North America

Length of growing season (days)	90
Growing degree units per growing season	1200
Minimum and base temperature	4°C
Maximum temperature	32°C
Mean minimum temperature in January	
Spring wheat	<-12°C
Winter wheat	≥-12°C
Vernalization requirement	
Winter wheat - at least one mean monthly surface temperature	≤5°C
Fall-sown spring wheat - mean monthly temperature for all months	>5°C
Annual Precipitation (mm yr^{-1})	
No wheat grown	≥1200
Soft wheat	760-1200
Hard wheat	0-760
Dry moisture conditions	0-380
Adequate moisture conditions	380-760

Source: Rosenzweig (1985)

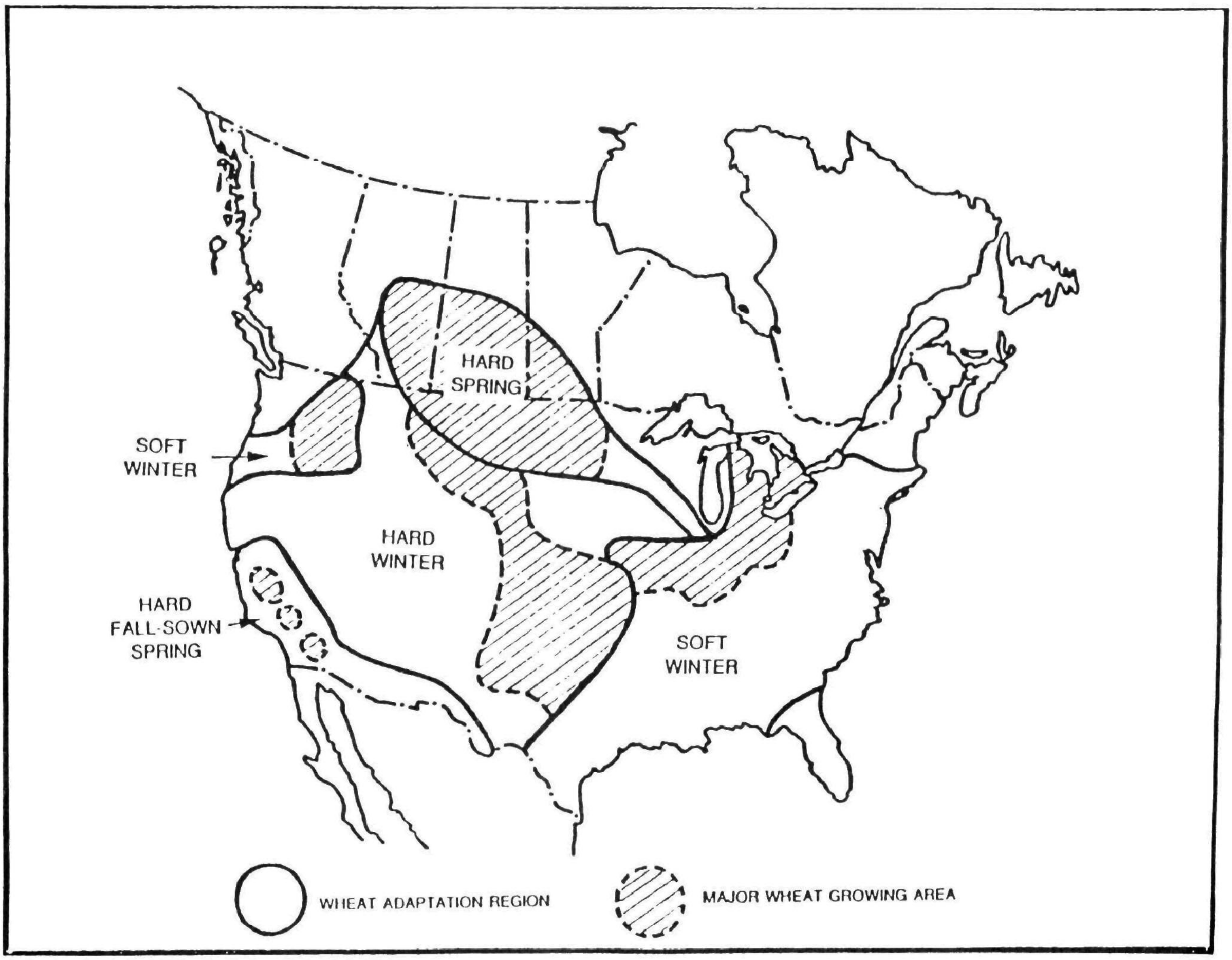

Figure 8. Major Wheat-Growing Areas of North America
Source: Rosenzweig (1985)

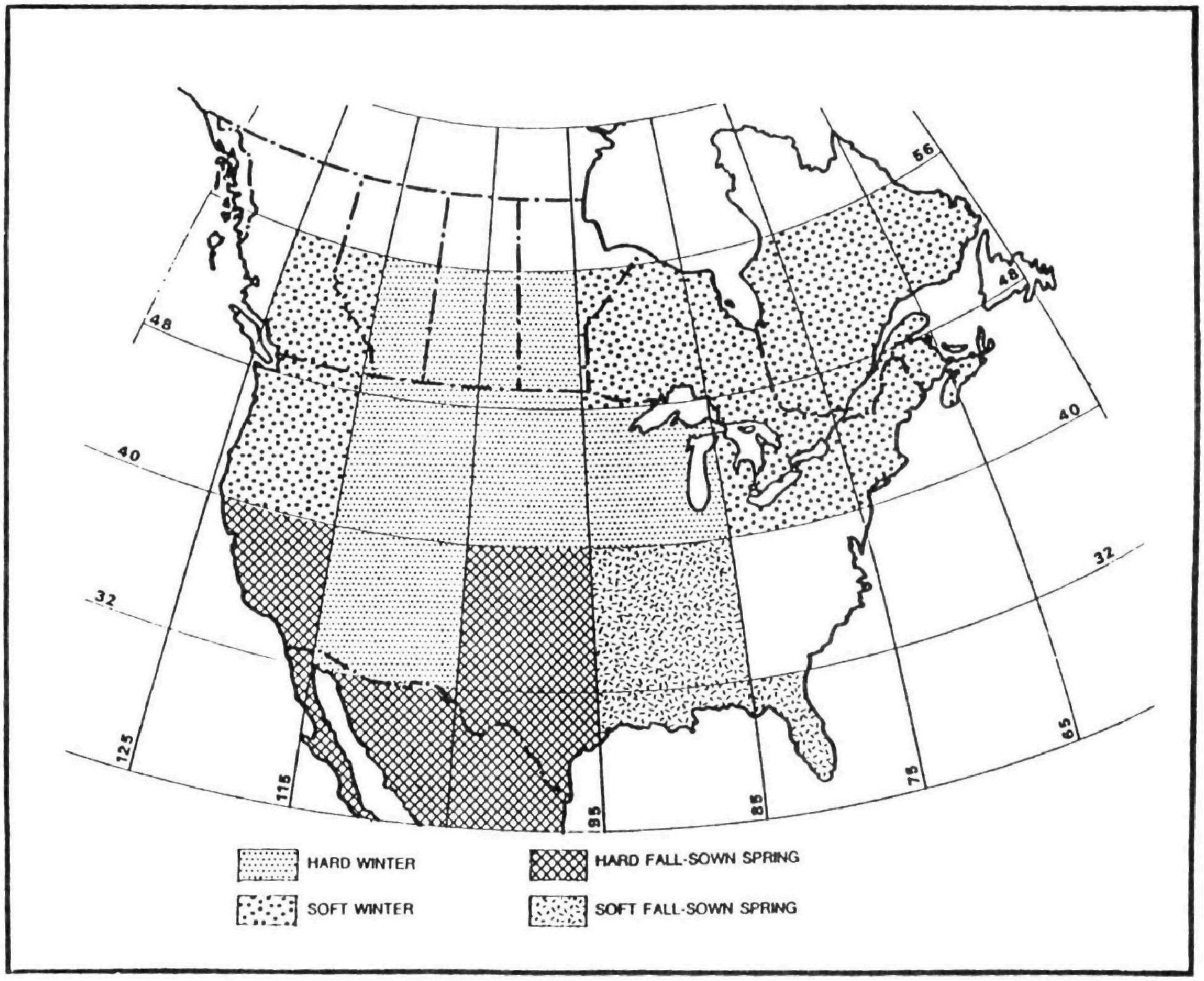

Figure 9. Simulated North American Wheat Regions Using the GISS-GCM
Source: Rosenzweig (1985)

fields shifted the wheat classifications in several grid squares just under or over the limit into the next category, and in this situation some wheat of each type might be present.

In the case of winter wheat expansion into Canada, the key to this is the change in mean minimum winter temperature. Currently, low temperatures affecting survival during winter are the major constraint. However, technological improvements in varieties and production techniques over the last decade appear to be overcoming the winter survival problem. For example, since 1976 winter wheat hectarage in the prairies has increased from virtually nothing to over 500,000 hectares in 1985 (Statistics Canada 1986). This expansion has also benefited somewhat from the climatic warming currently underway. Hansen et al. (1981), for example, have found evidence that global temperatures have risen about 0.2°C since the middle of the 1960s. Similar results have been recorded by Shewchuk (1984) for climatic analysis of the last two decades in Saskatoon, Saskatchewan. As a consequence, if the warming trend continues, it is not unreasonable to expect that the shift from spring wheat to winter wheat will continue, assuming new markets will be found and exploited. As to whether winter wheat would entirely replace spring wheat production, only time will tell. Certainly if summer droughts become more frequent and severe, logic would suggest that this would be the case. However, future market conditions, improvements in technology, and the possible development of more heat- and drought-resistant varieties in the future will ultimately determine this.

CONCLUSION

Results from this study suggest that the possible changes in the long-term climate of Saskatchewan resulting from the GISS general circulation modeling experiments for a doubling of atmospheric CO_2 would increase the annual growing season in the prairies by an average of 48 days and would increase precipitation from 11% to 14%. In conjunction with the increase in growing season length agricultural planting dates would be advanced by about three weeks and the fall harvest period would be extended by about four weeks. In total, the growing season climatic conditions throughout Saskatchewan would become more homogeneous.

In spite of the increased precipitation and enhanced CO_2 effect on photosynthetic capacity, the impact of the GISS CO_2 climate change would generally reduce spring wheat yields and production potential by 5% to 20% depending on whether projected GISS precipitation increases were attained or not. Any change in variability or reduction in precipitation from current levels could reduce production significantly.

Analysis of the projected GISS climate change for Saskatchewan suggests that the prairies would become more drought-prone with droughts occurring with greater frequency and severity. The effect of this is likely to be an increase in the variability in yields and production between years. A probable consequence of this situation in all likelihood will be a shift of the winter wheat belt from the U.S. into Canada. This is a likely conclusion strictly from the magnitude of the climate change postulated by the GISS model, which estimates a shift of the present climate of Nebraska to Saskatchewan. A shift to fall-sown crops in the existing agricultural area would enable farmers to take advantage of increased fall and early spring moisture levels. It would enable crops to develop and mature before the onset of drought conditions in June and July, which would be most damaging for spring-sown crops.

ACKNOWLEDGMENTS

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Potential Effects of Greenhouse Warming on Natural Communities[1]

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ABSTRACT

Previous natural climate changes have caused large-scale geographical shifts, changes in species composition, and extinctions among biological communities. If the widely predicted greenhouse effect occurs, communities will respond in similar ways. Moreover, population reductions and habitat destruction due to other human activities will make it difficult for species to shift ranges in response to changing climatic conditions. This paper identifies some groups of species at risk, including coastal species and remnant populations near the extremes of the original species ranges. Survival of many species will depend upon greater management responses than currently envisioned, including transplantation and in situ management.

As I did stand my watch upon the hill,
I look'd toward Birnam, and anon, methought,
The wood began to move.
Macbeth, Act V Scene V

Current human development and population trends suggest to all but the very optimistic that by the next century most other surviving terrestrial species may well be relegated to small patches of their original habitat, patches isolated by vast areas of human-dominated urban or agricultural lands. Without heroic measures of habitat conservation and intelligent management, hundreds of thousands of plant and animal species could become extinct by the end of this century (Myers 1979; Lovejoy 1980), with more to follow in the next. This diminution of biological diversity will have major consequences for human society.

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1 Adapted by the authors from BioScience 35:707-17, December 1985.

Many species will be lost because no habitat reserves are set aside for them, but even those within reserves will be threatened by a combination of genetic and ecological events (Diamond 1975; Soule and Wilcox 1980). Recent investigation into these events has provided insight into how reserves should be designed and managed (Frankel and Soule 1981; Schonewald-Cox et al. 1983; Soule and Wilcox 1980). But although the significance of future climate change to species survival has been independently mentioned by several authors (Ford 1982; Norse and McManus 1980; Wilcox 1980), little attention has been given to the impact on biological diversity of an increasingly likely event: global CO_2-induced climatic change, due to the greenhouse effect. If the greenhouse warming occurs, it will pose a new and major threat to species within reserves, species already stressed by the effects of habitat fragmentation.

Our understanding of how atmospheric composition affects global climate is still in its infancy, but an increasing body of knowledge suggests that several types of change affecting the survival of species--including a substantial global increase in temperature, a widespread alteration of rainfall patterns, and perhaps a rise in sea level--may be caused by rising concentrations of CO_2 and other anthropogenic polyatomic gases (Hoffman, Keyes, and Titus 1983; Machta 1983; Manabe, Wetherald, and Stouffer 1981; National Research Council 1983; Schneider and Londer 1984).

This paper identifies problems caused by climate change that affect biological communities, examines the particular difficulties faced by species in biological reserves, and suggests management options. Although we recognize that dealing with short-term extinction threats alone will strain the resources of conservationists, we feel that the possible negative effects of global warming could be so severe that conservation plans should be amended to reflect knowledge of climatic effects as soon as it becomes available. Decisions about the siting and design of reserves, and assumptions about how much management will be needed in the future, must reflect the increased economic and biological demands of global warming.

PATTERNS OF CLIMATIC CHANGES

Continued burning of fossil fuels, with a possible contribution from progressive deforestation, is increasing atmospheric CO_2 concentration that could reach double the concentration in 1880 within the next 100 years (Hansen et al. 1981; NRC 1983; Schneider and Londer 1984). The concentration of additional greenhouse gases, notably methane and chlorofluorocarbons, will also increase significantly as the result of human activities (Machta 1983; Ramanathan et al. 1985). Because the greenhouse gases absorb some of the upward infrared radiation from the ground, preventing its escape into space, the lower atmosphere will grow warmer. There is still a great deal of uncertainty about the greenhouse process, and predictions depend upon assumptions about future trends in fossil fuel use, the precise nature of the carbon cycle, and the complexities of atmospheric interactions. Nonetheless, most experts agree that globally the climatic average could warm by 1.5° to 4.5°C by the end of the next century (NRC 1983). Moreover, this change would likely be two or three times greater at the poles (Schneider and Londer 1984; see Figure 1a for one model's predictions).

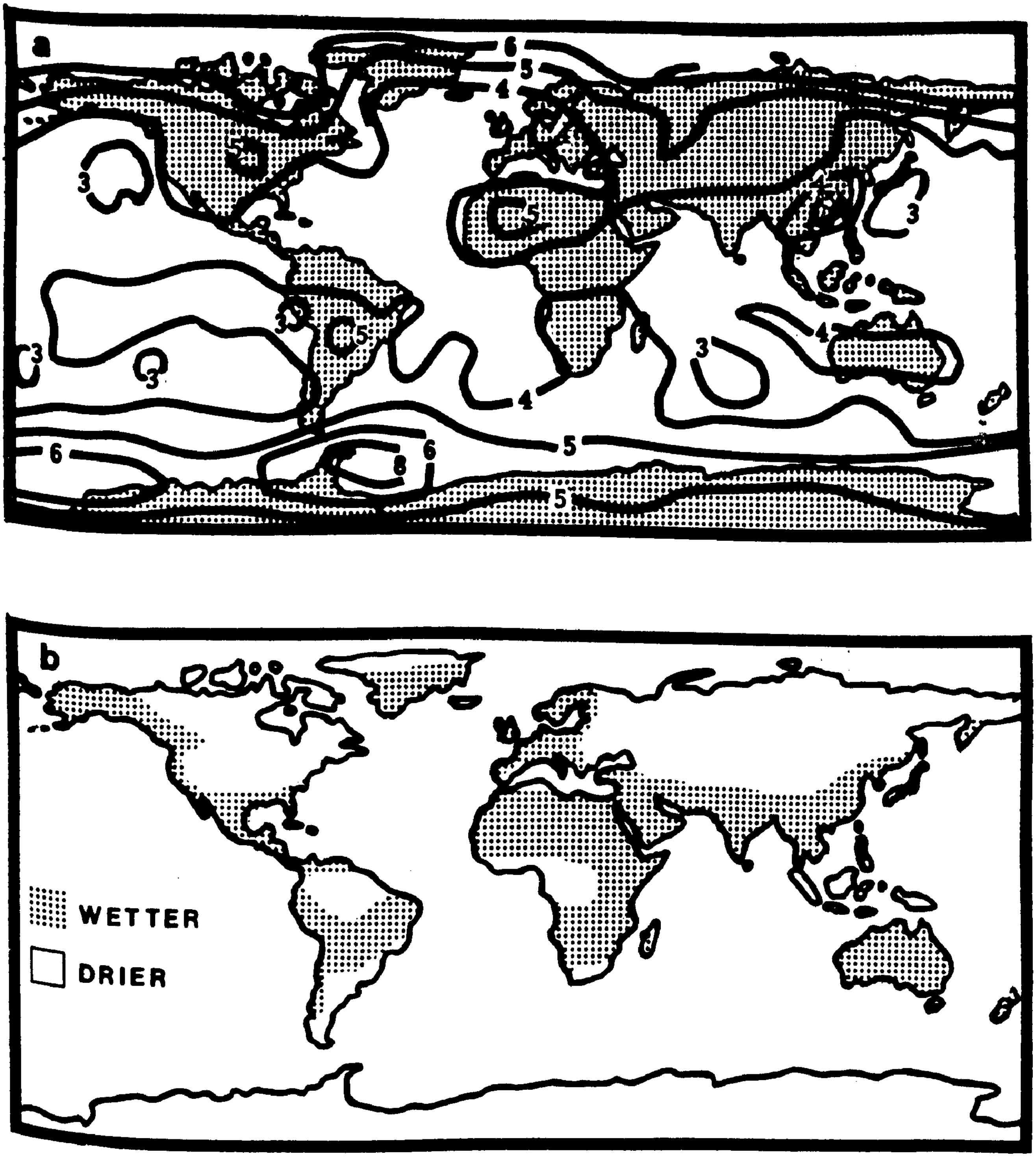

Figure 1. (a) Global patterns of surface temperature increase, as projected by the Goddard Institute for Space Studies (GISS) model (Hansen et al. 1985) in degrees C. (b) Global changes in moisture patterns (Kellogg and Schware 1981).

A change of this magnitude is large compared with normal fluctuations. For example, an increase of only 2°C over the current average global temperature would make the planet warmer than at any time in the past 100,000 years (Schneider and Londer 1984).

Furthermore, although CO_2 doubling would not be reached for some time, transient temperature increases occurring before doubling is reached might still have significant impact on biological systems. Indeed, if climatic models predicting the greenhouse effect are correct, warming distinguishable from normal climatic variation should occur within the next 10-15 years (Hansen et al. 1981; Madden and Ramanathan 1980) and may, in fact, already be observable (World Meteorological Organization 1982).

As important to biological communities as temperature change itself is that the projected increases in temperature would cause widespread changes in precipitation patterns (Hansen et al. 1981; Kellogg and Schware 1981; Manabe, Wetherald, and Stouffer 1981; Wigley et al. 1980). For many species, a change in water availability would have greater impact than temperature changes of the order predicted (e.g., Neilson and Wullstein 1983).

Although precise regional predictions of future precipitation patterns are yet to come, some attempts have been made to estimate large-scale changes. For example, in their model of future rainfall patterns, Kellogg and Schware (1981) suggest that the American Great Plains may experience as much as a 40% decrease in rainfall by the year 2040 (Figure 1b). In some areas increased evaporation caused by increased temperature could exacerbate regional drying (e.g., Manabe, Wetherald, and Stouffer 1981).

A rise in sea level resulting from thermal expansion of sea water and melting of glaciers and polar ice caps has been widely discussed as well, although such estimates of a rise vary. NRC (1983) has estimated a possible increase of 70 cm over the next century; another study projects a most likely rise of between 144 cm and 217 cm by 2100 (Hoffman, Keyes, and Titus 1983). If the western Antarctic ice cap melted, which is highly uncertain, rises of up to 5-6 m might occur over the next several hundred years (Hansen et al. 1981; NRC 1983).

In addition, the warming trend may alter the ocean's vertical circulation, causing change in the upwelling patterns that sustain many marine communities (Frye 1983; Kellogg 1983).

Finally, increased atmospheric CO_2 may result in more acidic, nutrient-poor soils (Kellison and Weir 1986). It may also change photosynthetic efficiencies, growth rates, and water requirements of different plant species in different ways (NRC 1983), thereby altering competitive outcomes (Strain and Bazzaz 1983) and possibly destabilizing natural ecosystems.

THE SPECIAL CASE OF BIOLOGICAL RESERVES

Such changes in important environmental parameters that determine the range of species would affect nearly all species, but the consequences would be most dire for those restricted to reserves or sharing characteristics of species restricted to reserves, notably limited range, small population, and genetic isolation. Populations within reserves, such as national parks, national forests, and wildlife refuges, will typically be remnants of larger original populations reduced through overharvesting or habitat loss and therefore will be subjected to a variety of threats more serious to them than to larger and more widespread populations.

Whenever the area that an original community of species occupies is reduced, as when a reserve is created and the land surrounding it is developed, some species are lost (Diamond 1975; Terborgh and Winter 1980; Wilcox 1980). Some disappear rapidly because the reserve does not include necessary resources; others are lost because any large-scale environmental change can cause extinction if the population is too localized; some vanish because of inbreeding and genetic drift.

As these environmental and genetic factors combine to cause the loss of some species, readjustment of mutualistic, parasitic, competitive, and predator-prey relationships among the remaining species must take place, most likely causing the loss of still others (e.g., Paine 1966). Climate change thus brings new pressures, including physiological stress and changes in competitive interactions, to bear on reserve species already stressed by a disequilibrated community. A common result of these climate-induced pressures would be further diminution of species' ranges and population sizes, which would in turn accentuate the various environmental and genetic effects associated with small populations, perhaps leading to extinctions.

Not only can the isolation of a population within a reserve surrounded by altered, unsuitable habitat mean it would receive little numerical or genetic augmentation from any populations outside the reserve, but the converse is also true. Isolated reserve populations could not respond to changing climatic conditions within the reserve by colonizing other "islands" of habitat outside the reserve where the climate is suitable.

Reserve species, which would generally be geographically localized, would be more likely to experience intolerable climatic changes throughout their ranges than would more widespread species. For example, a tree species whose entire range falls in an area due to undergo regional drying is more at risk than one whose larger range includes areas outside the desiccation zone. Further, remnant populations in reserves may represent only a fraction of the gene pool originally present in the species as a whole (Frankel and Soule 1981). Diminution of a species' range could mean the loss of populations adapted to particular climatic conditions, decreasing the genetic material that both nature and humans have to work with.

A climatic change would often improve conditions for a particular species at one margin of its range and worsen conditions at the opposite. Reserve populations located near a margin where conditions are deteriorating would therefore be more threatened than ones at the opposite end of the range (Figure 2).

COMMUNITIES RESPOND TO CLIMATE CHANGE

In the past, entire biomes have shifted in response to global temperature changes no larger than those that may occur during the next 100 years (Baker 1983; Bernabo and Webb 1977; Butzer 1980; Flohn 1979; Muller 1979; Van Devender and Spaulding 1979). In general, when temperatures have risen,

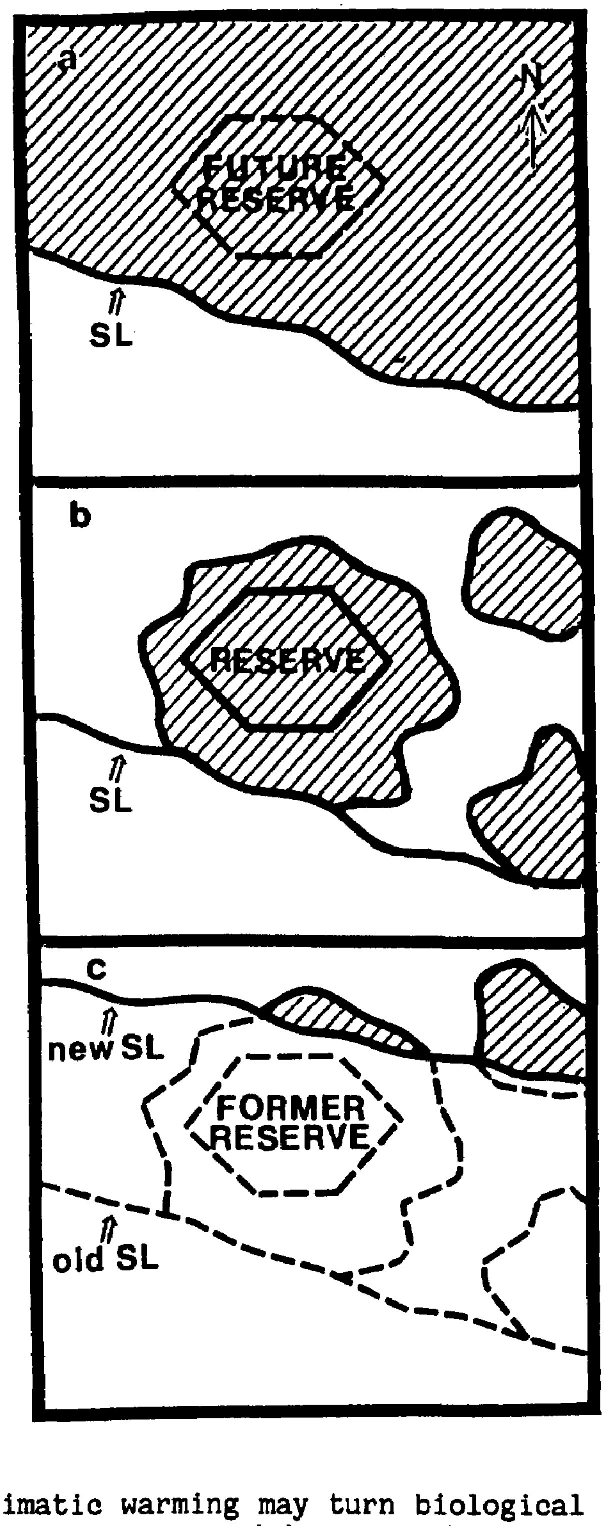

Figure 2. How climatic warming may turn biological reserves into former reserves. Hatching indicates: (a) species distribution before human habitation, southern limit, SL, indicates southern limit of species range; (b) fragmented species distribution after human habitation; (c) species distribution after warming.

species colonized new habitats toward the poles, often while their ranges contracted away from the equator as conditions there became unsuitable. Equatorial organisms thus expanded their ranges into areas previously tenanted by temperate ones, while temperate organisms did the same in some areas that had previously been the domain of boreal communities.

During several Pleistocene interglacials, for example, the temperature in North America was apparently 2°-3°C higher than now. Osage oranges and pawpaws grew near Toronto, several hundred kilometers north of their present distribution; manatees swam in New Jersey; tapirs and peccaries foraged in Pennsylvania; and Cape Cod had a forest like that of present-day North Carolina (Dorf 1976). Other significant changes in species' ranges have been caused by altered precipitation accompanying global warming, including expansion of prairie in the American Midwest during a global warming episode approximately 7000 years ago (Bernabo and Webb 1977).

Although Pleistocene and past Holocene warming periods were probably not due to elevated CO_2 levels, researchers have predicted that, if the proposed CO_2-induced warming occurs, similar species shifts would also occur, and vegetation belts would move hundreds of kilometers toward the poles (Frye 1983); 300 km is a reasonable estimate based on models (Miller, Dougherty, and Switzer 1986) and on the positions of vegetation zones during analogous warming periods in the past (Dorf 1976; Furley et al. 1983).

Although both the fossil record and current distributions demonstrate that many species have been able to shift successfully in response to such climate changes, many others have not, either because their rates of migration were too slow or because geographical barriers like oceans, mountains, or areas of inappropriate soil type prevented their reaching suitable habitats.

For example, a large, diverse group of plant genera, including water-shield (Brassenia), sweet gum (Liquidambar), tulip tree (Liriodendron), magnolia (Magnolia), moonseed (Menispermum), hemlock (Tsuga), arbor vitae (Thuja), and white cedar (Chamaecyparis), had a circumpolar distribution in the Tertiary. But during the Pleistocene ice ages, all went extinct in Europe while surviving in North America. Presumably, the east-west orientation of such barriers as the Pyrennes, Alps, and the Mediterranean, which blocked southward migration, was partly responsible for their extinction (Tralau 1973). In the case of reserve species, human modification of surrounding habitat will create barriers of agricultural or urban land which will be just as effective as mountains or oceans in preventing colonization of other suitable areas.

If global warming of 2°-3°C did occur by the end of the next century, it would be very rapid compared with some prehistoric changes of similar magnitude. In contrast, the change to warmer conditions at the end of the last ice age, considered rapid, spanned several thousand years (Davis 1983). The rate of change has profound significance for species survival, for even if suitable land is preserved for a species to shift to, extinction may still occur if present habitat becomes unsuitable faster than new habitat can be colonized.

The fossil record shows that dispersal rates have been crucial to species' ability to colonize suitable habitat during past climate changes.

For example, warm-temperate plant species were pushed south out of Great Britain and Ireland by cold during the Pleistocene. As the temperature increased, these plants later moved northward again, but only some dispersed rapidly enough to reach Great Britain before rising sea levels separated it from the European continent, and fewer could colonize Ireland before that island was separated from Britain (Cox, Healey, and Moore 1973). Other species that thrived in Europe during the cold periods, but could not survive the conditions in postglacial forests, could not extend their ranges northward in time and became extinct except in cold, mountaintop refugia (Seddon 1971).

If estimates of a several-hundred-kilometer poleward shift in temperate biotic belts during the next century are correct, then a localized population now living where temperatures are near its maximum thermal tolerance would have to shift northward at a rate of several kilometers per year to avoid being left behind in areas too warm for survival. Although some species, such as plants propagated by spores or dust seeds, may be able to match these rates (Perring 1965), many species could not disperse fast enough to compensate for the expected climatic change without human assistance, particularly given the presence of dispersal barriers. Even wind-assisted dispersal may fall short of the mark for many species. For example, wind scatters seeds of the grass Agrostis hiemalis, but 95% fall within 9 m of the parent plant (Willson 1983). In the case of the Engelmann spruce, a tree with light, wind-dispersed seeds, fewer than 5% of seeds travel even 200 m downwind, leading to an estimated migration rate of between 1 and 20 km per century (Seddon 1971). An extreme case is the double coconut (Lodoicea maldivica), whose giant seed can "only fall off the tree, and if the tree grows on a slope, roll downhill" (Willson 1983).

Although animals are mobile, the distribution of some is limited by the distributions of particular plants; their dispersal rates would thus largely be determined by those of co-occurring plants. Behavior may often restrict dispersal even of animals physically capable of large movements. For example, dispersal rates below 2 km/year have been measured for several species of deer, and many tropical deep-forest birds simply do not cross even very small unforested areas (Diamond 1975). On the other hand, some highly mobile animals, particularly those whose choice of habitat is relatively unrestrictive, may shift rapidly. Several authors (see Edgell 1984) have suggested, for instance, that climate change caused major range shifts in some European migratory waterfowl in this century.

Figure 3 illustrates the difficulties to be faced by a population whose habitat becomes unsuitable due to climate change. Propagules must run an obstacle course through various natural and human-created dispersal barriers in a limited amount of time to reach habitat that will be suitable under the new climatic regime. Dispersal ability will be crucial.

Because species shift at different rates in response to climate change, communities may disassociate into their component species (Figure 4). Recent studies of fossil packrat (Neotoma spp.) middens in the southwestern United States show that during the wetter, moderate climate of 22,000-12,000 years ago, there was not a concerted shift of communities. Instead, species responded individually to climatic change, forming stable, but by present-day standards, unusual assemblages of plants and animals (Van Devender and Spaulding 1979). In eastern North America, too, postglacial communities

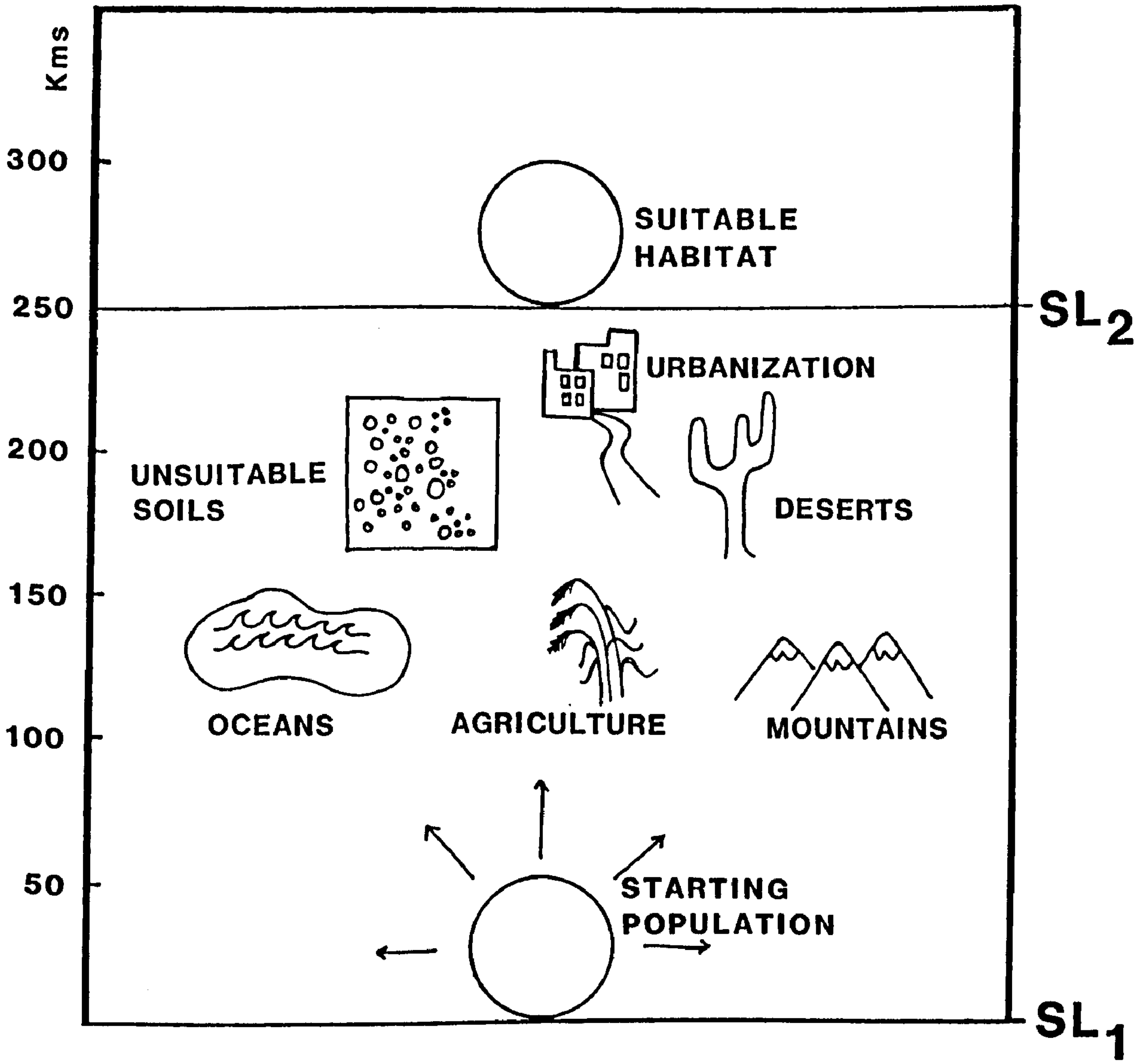

Figure 3. Obstacle course to be run by species facing climatic change in a human-altered environment. To "win," a population must track its shifting climatic optimum and reach suitable habitat north of the new southern limit of the species range. SL1 = species southern range limit under initial conditions. SL2 = southern limit after climate change. The model assumes a plant species consisting of a single population, which has its distribution determined solely by temperature. After a 3°C rise in temperature the population must have shifted 250 km to the north to survive, based on Hopkins bioclimatic law (MacArthur 1972). Shifting will occur by simultaneous range contraction from the south and expansion by dispersion and colonization to the north. Progressive shifting depends upon propagules that can find suitable habitat to mature and in turn produce propagules that can colonize more habitat to the north. Propagules must pass around natural and artificial obstacles like mountains, lakes, cities, and farm fields. The Englemann spruce has an estimated, unimpeded dispersal rate of 20 km/100 years (Seddon 1971). Therefore, for this species to "win," colonizing habitat to the north of the shifted hypothetical limit would require a minimum of 1,250 years.

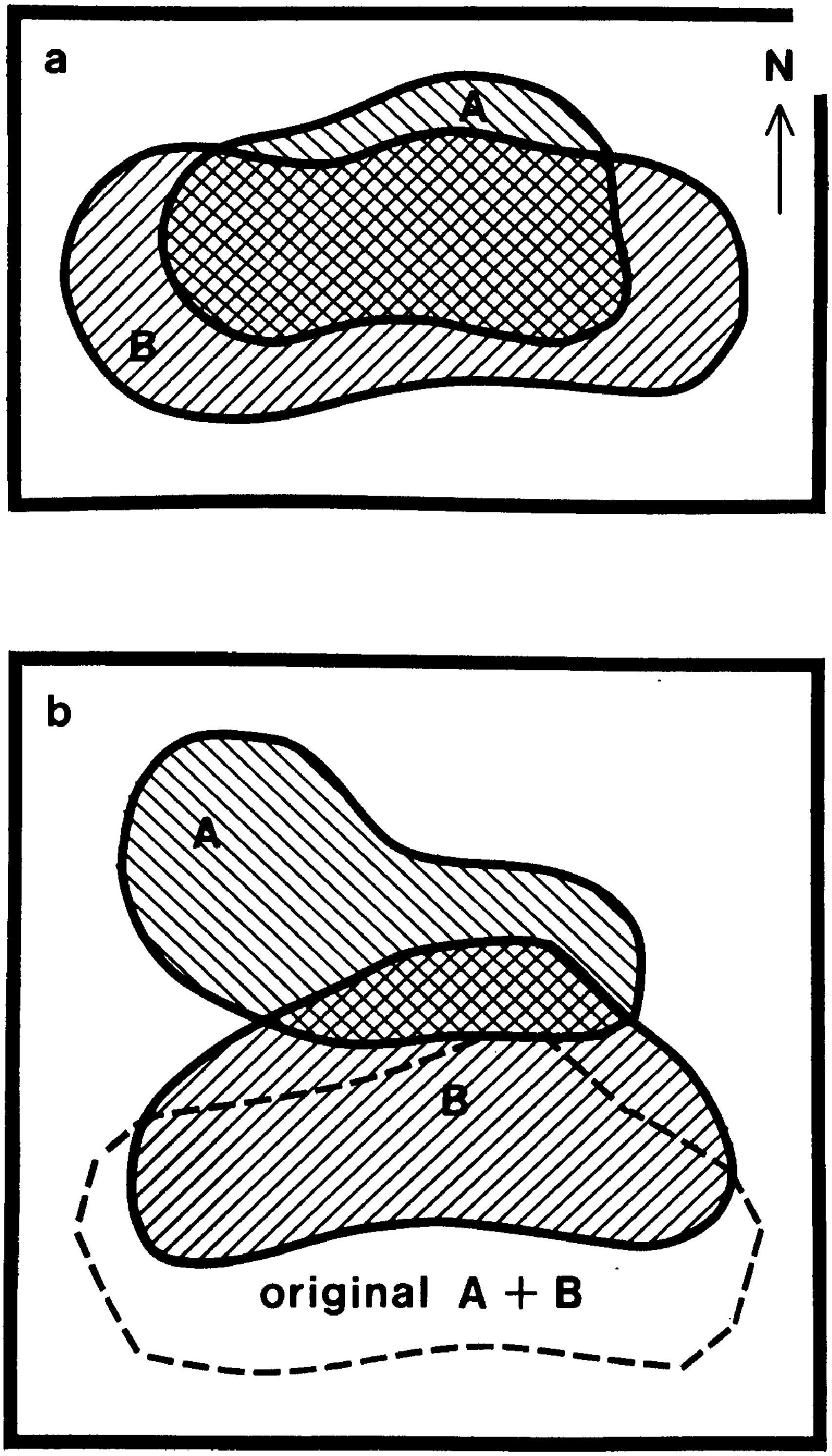

Figure 4. (a) Initial distribution of two species, A and B, whose ranges largely overlap. (b) In response to climate change, latitudinal shifting occurs at species-specific rates, and the ranges disassociate.

were often ephemeral associations of species, changing as individual ranges changed (Davis 1983).

An alternative to latitudinal shifting, even for species that cannot disperse rapidly, is to change altitude. Generally, a short climb in altitude corresponds to a major shift in latitude: the 3°C cooling of 500 m in elevation equals roughly 250 km in latitude (MacArthur 1972). Thus, during the middle Holocene when temperatures in eastern North America were 2°C warmer than at present, hemlock (Tsuga canadensis) and white pine (Pinus strobus) were found 350 m higher on mountains than they are today (Davis 1983). Similarly, species that could not shift poleward rapidly enough during a future warming trend to track a climatic optimum might be able to find sanctuary on mountains.

Underlying Biological Mechanisms

Climate change might cause local extinction in two interrelated ways. One is physiological: the climate of a formerly habitable area changes so it no longer corresponds to a species' physical tolerances. The other is interspecific: climate change alters interactions, such as predation or competition, so that a formerly successful species is eliminated from an area where it could physiologically survive.

Numerous examples of temperature's direct influence on species' distribution and survival exist. The direct range-limiting effects of excessive warmth include lethality, as in corals (Glynn 1984), and interference with reproduction, as in the large blue butterfly, Maculinea arion (Ford 1982). Moisture extremes exceeding physiological tolerances also determine species' distributions. Thus, the European range of the beech tree (Fagus sylvatica) ends to the south where rainfall is less than 600 mm annually (Seddon 1971), and dog's mercury (Mercurialis perennis), an herb restricted to well-drained sites in Britain, cannot survive a water table less than 10 cm below the soil surface (Ford 1982).

But in many cases, interspecific interactions altered by climatic change will have a major role in determining new species' distributions and, concomitantly, the susceptibility of species in reserves to extinction. Temperature can influence predation rates (Rand 1964), parasitism (Aho, Gibbons, and Esch 1976), and competitive interactions (Beauchamp and Ullyott 1932). For example, although the flatworm Planaria gonocephala is physiologically able to live when alone in streams of 6.5°-23°C, the presence of a competitor, P. montenigrina, excludes it from waters cooler than 13°-14°C. Because P. montenigrina cannot tolerate waters warmer than 13°-14°C, a warming trend would increase the habitat available to P. gonocepha (Beauchamp and Ullyott 1932). Similarly, the British plant oxlip (Primula elatior) can grow under a variety of moisture regimes, including dry sites, but it is excluded from dry sites by dog's mercury (Ford 1982).

Species may not only be threatened by competitors naturally occurring within a reserve, but they may also feel pressure from invaders that find the new climatic regime to their liking. For example, Melaleuca quinquenervia, a bamboo-like Australian eucalypt, has invaded the Florida Everglades, forming dense monotypic stands where drainage and frequent fires have disturbed the natural marsh community (Courtenay 1978; Myers 1983). Such invasions may become commonplace in response to large-scale climate changes, and controlling them is one of the major concerns of reserve managers (Goigel and Bratton 1983).

The underlying physiological adaptations of most species to climate are conservative, and it is unlikely that most species could evolve significantly new tolerances in the time allotted to them by the coming warming trend. The llama, for example, has water turnover rates as low as those of its relative the camel, even though the llama has lived in cold, wet environments for several million years (MacFarlane 1976). Indeed, the evolutionary conservatism in thermal tolerance of many plant and animal species--beetles, for example (Coope 1977)--is the underlying assumption that allows us to infer past climates from faunal and plant assemblages.

In contrast, some invertebrates have apparently adapted when introduced into new thermal environments. Several species of freshwater tropical invertebrates accidentally introduced into temperate waters survived initially only in artificially heated waters, such as power plant outflows, but were later found spreading into nonheated sites (Aston 1968; Ford 1982).

A Reserve Scenario

Because the ecological ties binding a species to its environment are so complex, the preceding physiological, interspecific, and genetic factors would combine to affect reserve populations confronted with climatic change.

Imagine a hypothetical situation where a single oxlip population is confined within a British reserve, excluded from the reserve's dry sites by a competitor, the dog's mercury. Then, because of global climatic changes, rainfall decreases within the reserve, allowing dog's mercury to displace the oxlip from an increasing number of its traditional sites.

At the same time, the ecological relationships of other species in the reserve are also changing, and some of these affect the oxlip. For example, a previously rare, second competitor of the oxlip undergoes a population explosion following the extinction of its major predator. In addition, a new insect herbivore introduced by humans finds the oxlip to its liking.

As the oxlip population becomes smaller and more fragmented from physiological stress, competitive exclusion, and increased predation, random environmental catastrophes and the inevitable genetic deterioration of small populations take their toll. Because the reserve population has been isolated from other populations outside the reserve, its genetic composition is relatively homogeneous to begin with and thus lacks the genetic variability to cope with the environmental threats. Moreover, no propagules from outside the reserve can bolster or reestablish populations where the oxlip becomes extinct.

When the oxlip disappears, other reserve populations, such as insect herbivores, that depend on the oxlip will also decline. Even a decrease in the oxlip population that falls short of extinction may cause extinction of species depending on it for food.

Although this scenario is hypothetical, such complex interplay leading to extinction can be seen today. For example, the two southern subspecies of the northern flying squirrel, Glaucomys sabrinus fuscus and G.s. coloratus, are confined as glacial relicts to several boreal populations in the Appalachian Mountains. They are increasingly endangered by both human-caused habitat loss and encroachment into their range by the southern flying squirrel, Glaucomys volans, which outcompetes them in the deciduous forests that are replacing the boreal conifers in retreat because of harvesting and climatic warming. The endangered subspecies are further threatened by a nematode parasite, which kills them but not the southern flying squirrel, its primary host (Handley 1979). Additional climatic warming may expand the range of the southern flying squirrel at the expense of the northern subspecies, hastening their decline.

Communities at Risk

Although many reserve communities would suffer from changing climates, we theorize that the following types of species and communities may be particularly affected by warming trends over the next 100 years:

Peripheral Populations. Populations located near the edge of a species range that is contracting in response to climate change would be at greater risk than those at the center or an expanding edge (see Figure 2).

Geographically Localized Species. Even if their populations were large, species whose geographic range is small to begin with, such as many reserve species, would be less likely to have any populations in areas of suitable habitat after a climate change than those whose distribution is more widespread (Beardmore 1983). Island species are a special case of geographically restricted species. If the latitudinal migration required of them exceeds the size of the island, a climate change would leave little alternative but extinction. However, climatic changes on oceanic islands might be relatively mild because the sea would moderate the air temperature.

Genetically Impoverished Species. Species that are reduced to small populations or whose ranges are severely curtailed may lose the genetic diversity, including ecotypes adapted to particular climatic conditions, needed to successfully respond to climatic change. Thus, projected climate change provides yet another reason to retain as much genetic diversity as possible within a species.

Specialized Species. Such species are generally less tolerant of ecological change because, by definition, some aspect of their life requires a narrow range of environmental conditions, conditions that might not exist during the ecological perturbations of a major climatic change. Often the survival of a specialist is tied to the survival of one or a few other species, as in the Everglades kite (Rostrhamus sociabilis), which depends on the apple snail (Pomacea caliginosa) as its single food source. The snails are themselves localized in range, and a decrease in their abundance due to drying of the Everglades has threatened the kite with extinction in the United States (Bent 1961). Future saltwater incursion into the swamps or decreases in rainfall could further threaten the kite.

Poor Dispersers. During past periods of climatic change, different species expanded their ranges at highly individual rates. For example, sugar maple (Acer saccharum), hickories (Carya spp.), oaks (Quercus spp.), and elms (Ulmus spp.) spread northward rapidly in eastern North America during the postglacial early Holocene. Chestnut (Castanea dentata) spread much more slowly, apparently because its self-sterility made it difficult to establish by seed (Davis 1983). The increasingly disjunct distribution of suitable habitat may make it very difficult for species not adapted for colonization to spread to new areas if the climate changes.

Annuals. Another interesting possibility is that annual and perennial species would differ in their ability to persist in reserves when confronted by climatic change. Complete reproductive failure in a given year by an annual species within a reserve spells local extinction unless propagules either remain dormant until a more favorable year or arrive from sources outside the reserve. Because many annual species are efficient dispersers and colonizers, with long-lasting propagules, these strategies may succeed. A perennial with equal dispersal abilities, however, has an advantage over annuals because the parent population can often survive conditions unsuitable for the establishment of young (e.g., Banus and Kolehmainen 1976), possibly for a number of years, until conditions become favorable for reproduction.

Whatever the case with annuals, some evidence suggests that species that depend on annual hosts run a greater risk of local extinction than those that depend on perennials. For example, Ehrlich et al. (1980) found that populations of the checkerspot butterfly Euphydryas editha relying on annual plant hosts apparently suffered a higher rate of local extinction during climatically unfavorable years than did those relying on a perennial host.

Montane and Alpine Communities. Because mountain peaks are smaller than bases, as species shift upward in response to warming, they typically occupy smaller and smaller areas, have smaller populations, and may thus become more vulnerable to genetic and environmental pressures. And because mountain populations are relatively isolated from other populations of the same species on other mountains, recruitment and recolonization would be difficult except for highly mobile species. Species originally situated near mountaintops might have no habitat to move up to and may be entirely replaced by the relatively thermophilous species moving up from below (Figure 5). Examples of past extinctions attributed to upward shifting by communities include alpine plants once living on mountains in Central and South America, where vegetation zones have shifted upward by 1000-1500 m since the last glacial maximum (Flenley 1979; Heusser 1974).

An interesting analogy to alpine species are those species living in other types of cold refugia that would also shrink as the climate warmed. For example, the northern Gulf of California contains a fauna distinct from that of the southern gulf. Several endemic isopods survive in the north, apparently because a cold local climate protects them from the tropical fish predators that occur throughout the rest of the gulf (Wallerstein and Brusca 1982). If the climate warms, however, these fish may extend their range into the cold refugium.

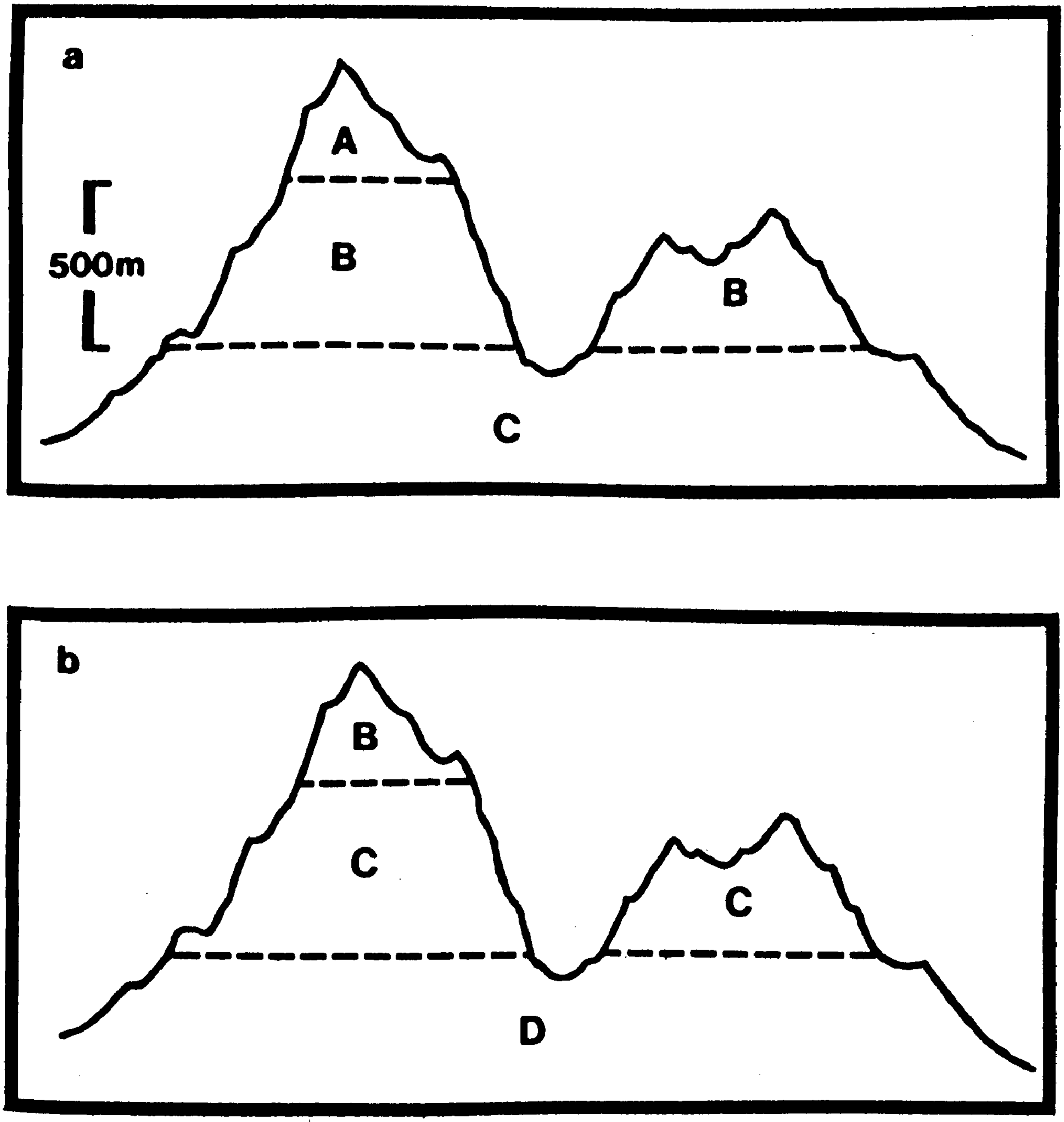

Figure 5. (a) Initial altitudinal distribution of three species, A, B, C. (b) Species distribution after a 500 m shift in altitude in response to a 3°C rise in temperature (based on Hopkin's bioclimatic law; MacArthur 1972). Species A becomes locally extinct. Species B shifts upward, and the total area it occupies decreases. Species C becomes fragmented and restricted to a smaller area, while species D successfully colonizes the lowest altitude habitats.

Arctic Communities. Because temperatures in arctic regions may increase more than in areas closer to the equator (Hansen et al. 1986), arctic species possibly may undergo greater physiological and competitive stress. On the other hand, many arctic species have adapted to withstand very large annual fluctuations in temperature, and so a sizable temperature change may be tolerated.

Coastal Communities. Many coastal species, like marine mammals and birds, depend on the rich food sources supported by coastal upwelling. The coastal communities they belong to may be disrupted if, as has been suggested (Frye 1983; Kellogg 1983), upwelling patterns are altered by global warming. That changes in upwelling may provoke widespread disruption has been demonstrated by recurrent El Nino events (e.g., Duffy 1983).

If those predicting sea-level rise are correct, much coastal habitat, like saltwater marshes and inlets used by nesting birds, may be inundated or eroded. With no development, coastal communities would shift upland as the sea rose, but human development of land above present high water may preclude this. In a study for the EPA, Kana, Baca, and Williams (1986) concluded that losses of wetlands around Charleston, South Carolina, could be severe--40%-80%--in the face of a rapidly rising sea level, but they will be even worse--approaching 100%--if bulkheads are built to protect the area that is now highland.

Freshwater lowlands along the coast would also be likely to suffer from the intrusion of salt water. The cypress trees of the U.S. Gulf Coast, for example, do not tolerate salt water, yet they grow only slightly above sea level (Titus, Henderson, and Teal 1984). (See Titus, Volume 1 and Park et al., Volume 4 for additional discussion of the impacts of sea-level rise on costal marshes.)

WHAT THIS MEANS FOR MANAGEMENT

Preventing global warming would be the most environmentally conservative response. Granted, this would be difficult, not only because fossil fuel use will increase as the world's population grows, but also because effective action would demand a high degree of international cooperation. If efforts to prevent global warming fail, however, and if global temperatures continue to rise, then ameliorating the negative effects of climatic change on biological resources will require substantially increased investment in reserve purchase and management.

To make intelligent plans for siting and managing reserves, we need more knowledge. We must refine our ability to predict future conditions in reserves. We also need to know more about how temperature, precipitation, CO_2 concentrations, and interspecific interactions determine range limits (e.g., Picton 1984; Randall 1982) and, most important, how they can cause local extinctions. Adequately understanding the influences of climate on population dynamics may require long-term studies of reserve populations, studies similar to Ehrlich's two decades of research on checkerspot butterflies (Ehrlich 1965; Ehrlich et al. 1980).

In addition to basic research, reserves that suffer from the stresses of altered climatic regimes will require carefully planned and increasingly intensive management to minimize species loss. For example, modifying conditions within reserves may be necessary to preserve some species, depending on new moisture patterns, irrigation or drainage may be needed. Because of changes in interspecific interactions, competitors and predators may need to be controlled and invading species weeded out. The goal would be to stabilize existing community composition by forestalling both succession and habitat deterioration, much as the habitat of Kirtland's warbler is periodically burned to maintain pine woods (Leopold 1978).

If such measures are unsuccessful, and old reserves do not retain necessary thermal or moisture characteristics, individuals of disappearing species may have to be transferred to new reserves. For example, cold-adapted ecotypes or subspecies may have to be transplanted to reserves nearer the poles. Other species may have to be reintroduced in reserves where they have become temporarily extinct. An unusually severe drought, for example, might cause local extinctions in areas where a species ordinarily could survive with minimal management. Such transplantations and reintroductions, particularly involving complexes of species, will often be difficult, but applicable technologies are being developed (Botkin 1977; Lovejoy 1985).

To the extent that we can still establish reserves, pertinent information about changing climate and subsequent ecological response should be used in deciding how to design and locate them to minimize the effects of changing temperature and moisture. In many areas of the Northern Hemisphere, for example, where northward shifts in climatic zones are likely, it makes sense to locate reserves as near the northern limit of a species' range as possible, rather than farther south, where conditions are likely to become unsuitable. Again, plans to reserve certain shallow alkali lakes in the Great Plains for the endangered piping plover, Charadrius melodus (Chipley 1983), could perhaps incorporate information on potential effects of the future decreases in precipitation that may occur in this area (Kellogg and Schware 1981).

It is often suggested that reserves might best be placed in areas of high species endemism, like the presumed Pleistocene refugia of South America, which are often interpreted as areas where many species successfully survived and diversified during past periods of drying (Terborgh and Winter 1983). Siting reserves in such areas maximizes the number of endemic species saved in each reserve. A similar good argument for cost-effectiveness can be made for areas of high species diversity. In either case, knowing the long-term effects of future local climate would be invaluable in determining whether a species- or endemic-rich reserve is indeed suitable for the long-term survival of the species within.

Locating reserves where topography and soil types are heterogeneous could increase the chance that a species' precise temperature or moisture requirements would be met. Wilcox and Murphy (1985) have shown that populations of a checkerspot butterfly survive longer under normal climatic fluctuations if they inhabit several slopes that face different directions and thus have different moisture characteristics. Altitudinal variability within a reserve would increase the chance that vertical shifting could occur. Fortunately, many reserves have been placed in mountainous land because such areas are generally less suitable for agriculture.

Maximizing the size and number of reserves would enhance the long-term survival of species. In large reserves, species would have a greater chance of finding suitable microclimates or of shifting altitudinally or latitudinally. If we could increase the number of reserves so that each species and community type were represented in more than one reserve, we would increase the chance that if the climate in a reserve became unsuitable, the organisms within it might still survive elsewhere.

Flexible zoning around reserves could preserve an option to shift reserve boundaries in the future, as, for example, by trading pasture land for reserve land. The multiuse, multizoned biosphere reserves now being set up in some countries, such as India (Saharia 1986), provide models of the sort of flexibility needed.

The unique situation of each reserve will challenge managers and planners to produce further ideas for maintaining biological diversity, and their task will be made more difficult by how fast changes are likely to occur. If we wait until we can predict exactly which parts of the world will be wetter or drier, for example, it will be too late--too late to begin the time-consuming task of setting up alternative reserves, too late to begin studying the effects of climate on competitive interactions, too late to identify those species most vulnerable to climatic change.

If we are concerned with setting up reserves and maintaining biological diversity--not just to eke out another 50 years or so of species survival but to preserve some remnants of the natural world for the year 2100 and beyond--we must begin now to incorporate information about global warming, as it becomes available, into the planning process.

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WATER RESOURCES

The Effects of Climate Change on the Great Lakes

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INTRODUCTION

This paper presents a few tentative answers, and a lot of questions, regarding CO_2-induced climatic change and its potential impacts on the biophysical and socioeconomic environments of the Great Lakes region. The research involves atmospheric sciences, hydrology, and a wide range of other fields, including agriculture, forestry, wetlands ecology, fisheries, shipping, energy, tourism and recreation, economics, and political science. Some of these impacts directly link to climatic change. Other impacts result from changes in the environment caused by climatic change, and so indirectly link to climate. These impacts include spinoff effects on water distribution systems, regional employment patterns, personal income, and costs of goods and services.

The purpose of this discussion is to present a status report, a review of what we know (or think we know) about future climate and its impacts on the Great Lakes, and a listing of areas where more research is needed.

CLIMATE AND HYDROLOGY

Status Report

Climatic fluctuations have a significant effect on Net Basin Supply (NBS) and lake levels. In this discussion, it is assumed that for the entire basin,

$$NBS = P(lake) - E(lake) + R$$

where P(lake) is lake precipitation, E(lake) is lake evaporation, and R is runoff from land. P(lake) is estimated from shoreline stations. E(lake) is estimated from a mass transfer model, using ship observations of lake temperature, wind speed, and air temperature. R is obtained using the Thornthwaite water balance approach. Existing diversions and groundwater are assumed to have minor importance at this scale.

Examination of the historical record shows that air temperature was relatively high during the 1930-60 period, and has been cooler since then. Precipitation has been high since 1940 (Quinn 1981), except in 1963 when low rainfall led to a sharp reduction in streamflow and lake levels. We will return to this later.

Climate change scenarios, based on general circulation models (GCM) of a doubled CO_2 environment, indicate higher air temperature and precipitation for the basin. Preliminary calculations indicate a significant decline in mean NBS to 1963-65 levels, because of projected increases in E(lake), for which the increase in precipitation would be insufficient to match. These computations, however, are highly dependent on assumptions about wind speed over the lake and lake surface temperatures which affect the dew point.

Figure 1 shows the Great Lakes study area. Calculations were performed using two scenarios of CO_2-induced climatic change obtained from GCMs: GISS (Goddard Institute for Space Studies) and GFDL (Geophysical Fluid Dynamics Lab). Grid points are shown on the map.

Calculations of E(lake) for Lake Erie for GISS and GFDL are shown in Figure 2 as S and L, respectively. The various S and L, scenarios include changes in wind speeds and vapor pressure (VP) as follows: G (normal wind and VP), 1 (80% normal wind), 2 (GFDL wind scenario), 3 (110% normal VP), 4 (90% normal VP), 5 (GFDL wind scenario and 110% normal VP), and 6 (GFDL wind scenario and 90% normal VP). A mass transfer model was used in which E(lake) is directly related to wind speed and the magnitude of the lake-air VP gradient (VPD). Higher VP in the overlying air, i.e., higher relative humidity, would reduce VPD, thereby reducing E(lake). The reverse would occur with lower relative humidity.

Data for calculations of present normals were obtained from the MAST archive of ship data (M), located at the Canadian Climate Centre, Downsview, Ontario. Two estimates using land stations are also shown (A1, A2). These require the use of lake/land ratios to estimate lake data. The newer estimates (A2) use stability-dependent ratios of wind speed, VP, and mass transfer coefficients, and also account for changes in ice cover. The new values are closer to those using ship data than the old estimates.

Results show significant increases in E(lake), especially for GISS, even if we assume present normal wind speeds and VPD (GS in Figure 2). If we change the wind speed and VPD, the results change. The GFDL wind scenario (decreased wind speeds in fall, increases and decreases in other months) leads to higher E(lake), but not as high as in the calculation with present normal winds. Lower VPD (S3, S5, L3, L5), due to higher surface VP, would actually reduce E(lake) to below present normals. The greatest departure from present E(lake) is obtained with reduced VP and either present normal winds (S4, L4) or the GFDL wind scenario (S6, L6).

Similar results are obtained for the entire Great Lakes (Figure 3). GS shows greater increases than GL. S4, S6, L4, and L6, the scenarios which include lower VP and either present normal winds or GFDL winds, lead to the largest increases in E(lake).

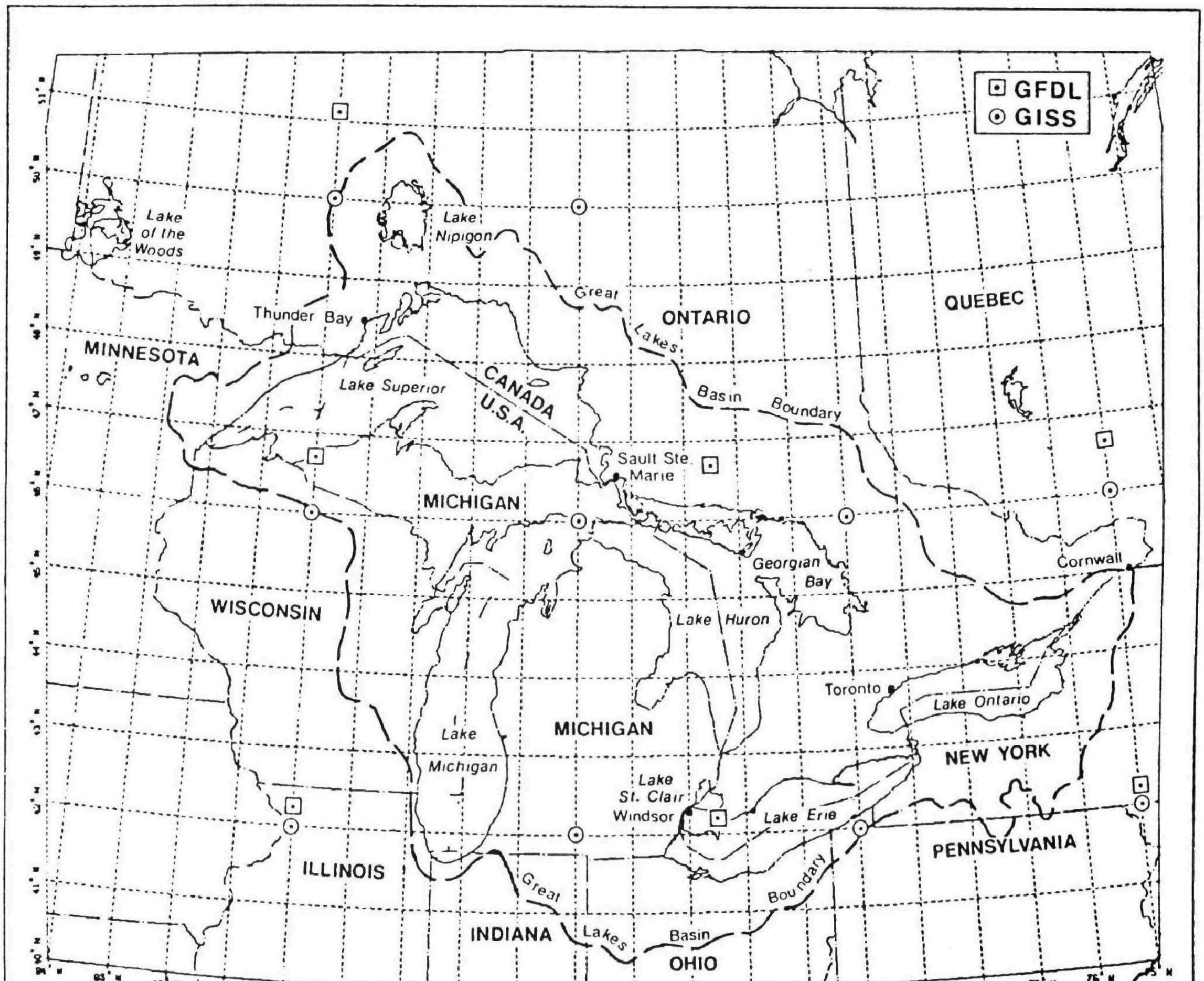

Figure 1. Great Lakes Study Area for GISS and GFDL General Circulation Models

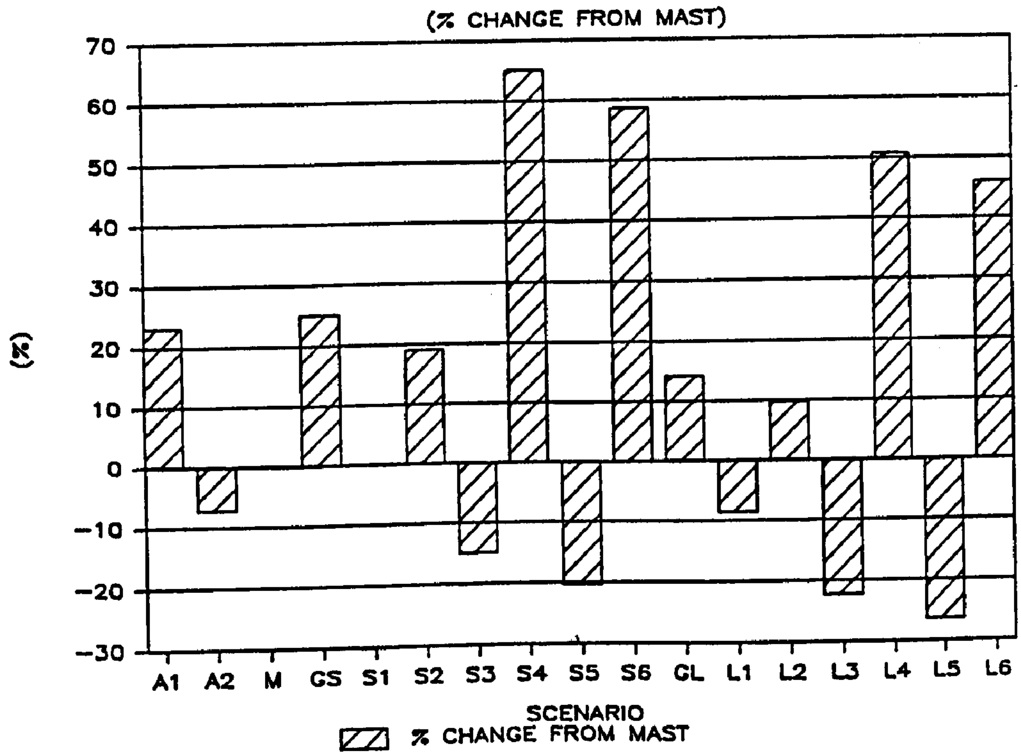

Figure 2. Lake Erie Evaporation for Various Scenarios

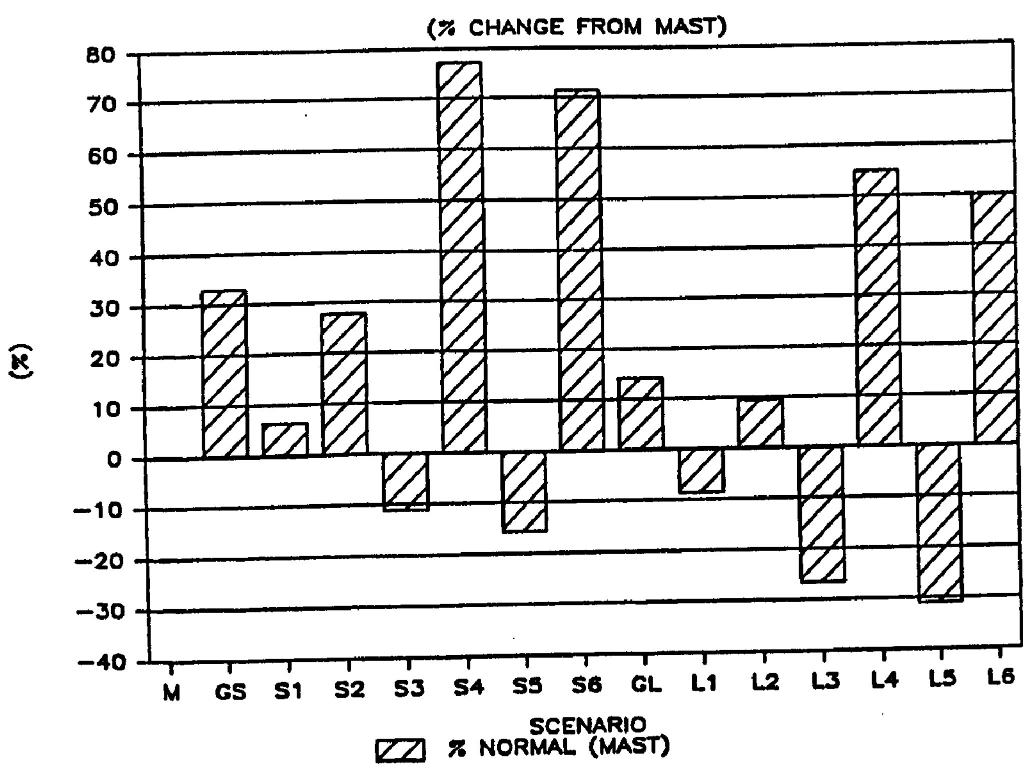

Figure 3. Great Lakes Evaporation for Various Scenarios

The above calculations are highly speculative because of a number of factors, including the following:

- GCMs have coarse resolution, and at present they do not include mesoscale lake effects.

- The evaporation "scenarios" are based on crude assumptions about changes in lake temperatures, ice cover, and wind speed.

The calculation of changes in NBS is also influenced by assumptions about P(lake). If we assume that P(lake) = 0.92 P(land), as indicated by the International Field Year for the Great Lakes (IFYGL) study in 1972 (Wilson and Pollock 1981), and that precipitation from the GISS and GFDL models represent P(land), we get the results shown in Table 1. Actual evapotranspiration from the land area, snowmelt, runoff, and soil moisture deficit were obtained using the Thornethwaite water budget model. Both scenarios point to warmer conditions with lower snowmelt and runoff, and to higher soil moisture deficits, despite the increased precipitation. Significant decreases in NBS are projected, but it is apparent that assumptions about wind speed (which affect lake evaporation estimates) have a significant influence on the results. In addition, estimates of present and future water consumption are uncertain (Cohen 1986a,b).

Similar difficulties exist when assessing CO_2-induced climatic change over the land portion of the basin. The coarse resolution of GCMs forces the climatologist to interpolate when estimating changes in snow cover or impacts on crop productivity, forest fire hazard, and outdoor recreation. A recent study by Crowe (1985) used present normals from operating stations to estimate snowfall changes for 173 grid points in southern Ontario, although there are only 4 grid points for GFDL and 6 for GISS in or near the region. Interpolation using present normals forces us to assume that local synoptic conditions will not significantly change in the future (e.g., timing and frequency of weather types). Will future regional climate include fewer episodes of frontal passage and increased convective activity? Would that alter the spatial distribution of precipitation within the region?

One approach to answering questions about future regional climate is to look at historical analogues. For example, what were conditions during 1963-65 when lake levels and NBS were almost as low as those predicted in Table 1 (Figure 4)? Over the land area, air temperatures at Sault Ste. Marie were above normal in most months between April 1963 and July 1964 (Figure 5). Basin precipitation was considerably below normal in 1963 (Figure 6). In Windsor, a six-month period of below-normal precipitation extended from July to December 1963 (Figure 7). Generally, 1965 was colder (e.g., Figure 5), but not significantly wetter than normal in all areas (e.g., Figures 7 and 8). The central region did experience increased precipitation (e.g., Figure 9).

As for conditions over the lakes themselves, the picture is incomplete, since records based on ship data are only available beginning in 1965. Lake temperatures that year were generally lower than normal (Figure 10). No clear trend appeared for wind. VP appeared to be higher in late fall-early winter, but very little data were available to reach firm conclusions.

Table 1. Effects of Climatic Change Scenarios on Annual Water Balance of the Great Lakes Basin

CLIMATE CONDITION	GISS	GFDL
Temperature Change	+4.3 to +4.8 C	+3.1 to +3.7 C
Precipitation	+6.4%	+0.8%
Actual Evapo-transpiration	+18.1%	+6.7%
Snowmelt	-45.9%	-35.8%
Runoff	-10.9%	-8.2%
Soil Moisture Deficit (summer)	+116.4%	+166.2%
NBS (present normal winds)	-20.8%	-18.4%
NBS - consumptive use (2035 proj.)	-28.9%	-26.4%
NBS (80% winds)	-4.1%	-4.0%
NBS (80% winds) -consumptive use (2035 proj.)	-11.8%	-11.7%

Source: Adapted from Cohen (1986b).

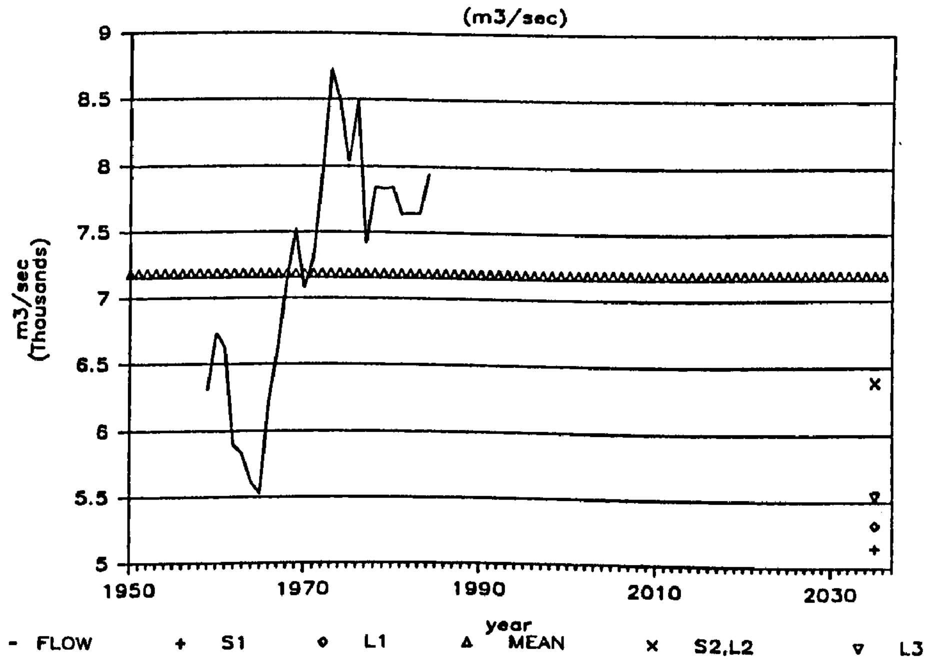

Figure 4. Historical and Projected Streamflow at Cornwall

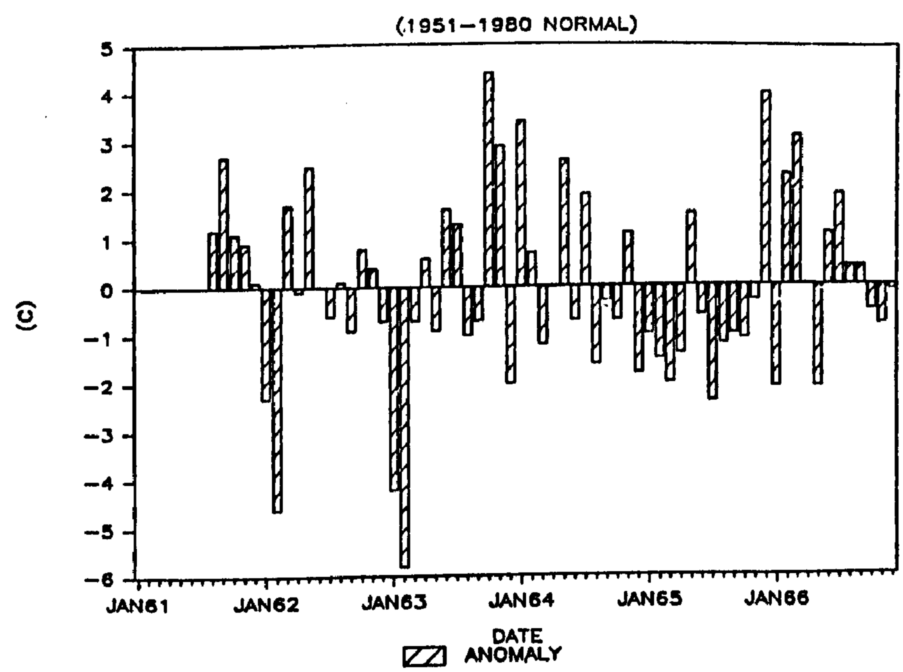

Figure 5. Monthly Temperature Anomalies, Sault Ste. Marie, 1961-1966

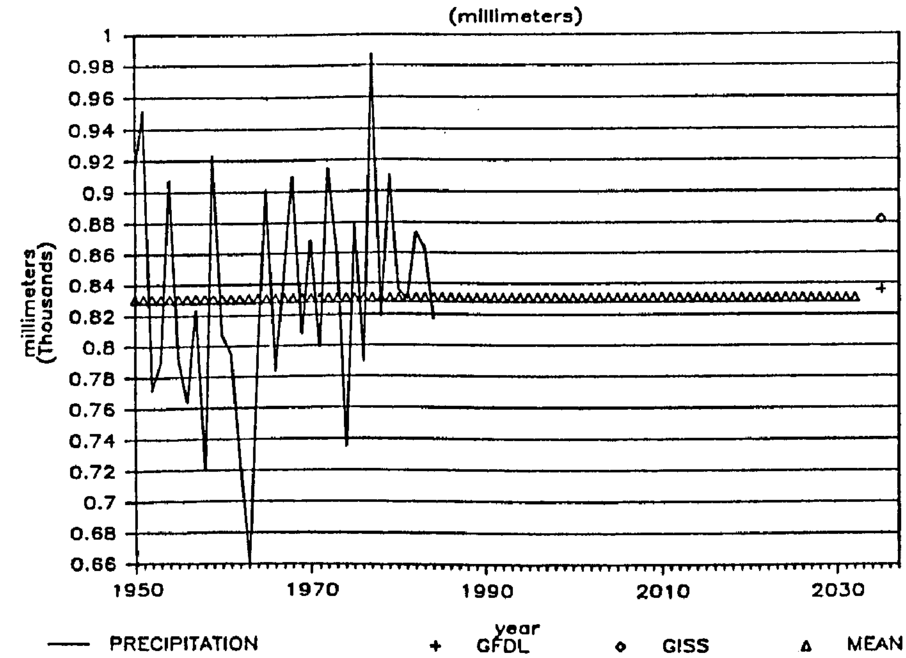

Figure 6. Annual Precipitation, Great Lakes Basin. Adapted from Quinn (1981 and personal communication) and Cohen (1986a)

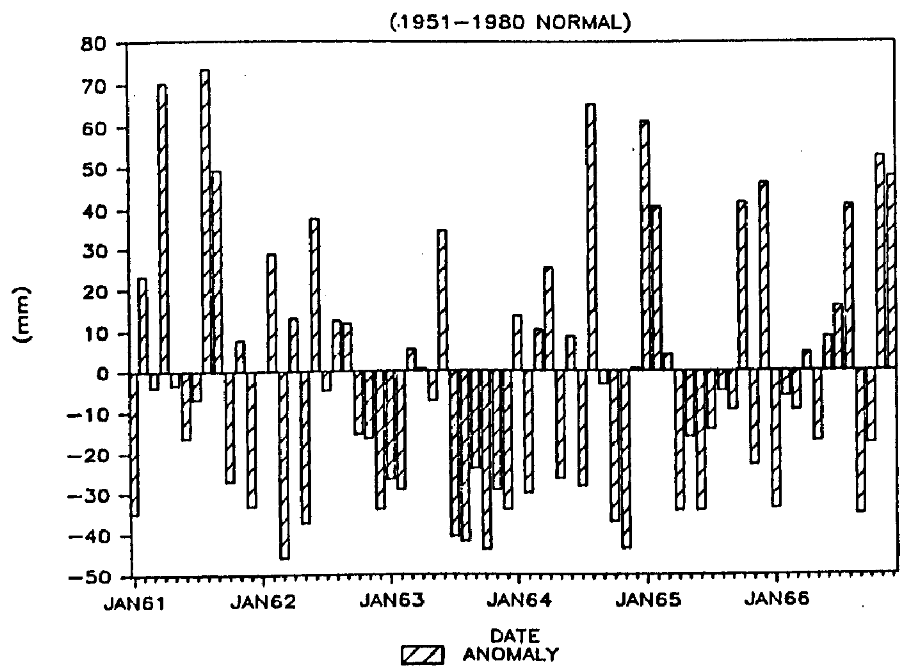

Figure 7. Monthly Precipitation Anomalies, Windsor, 1961-1966

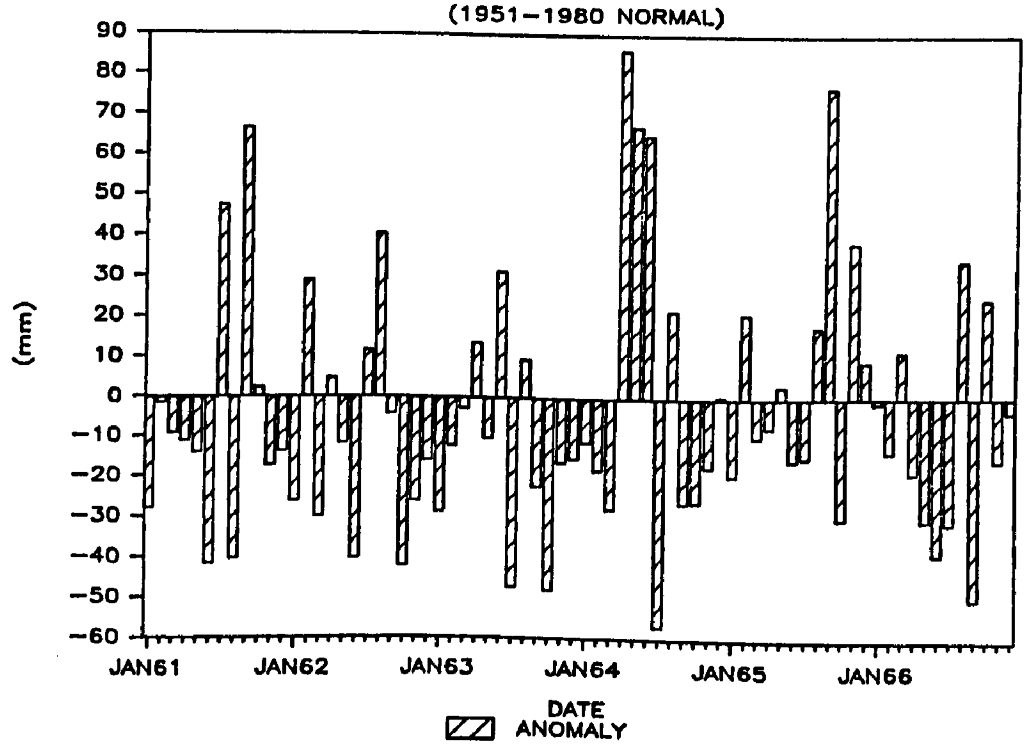

Figure 8. Monthly Precipitation Anomalies, Thunder Bay, 1961-1966

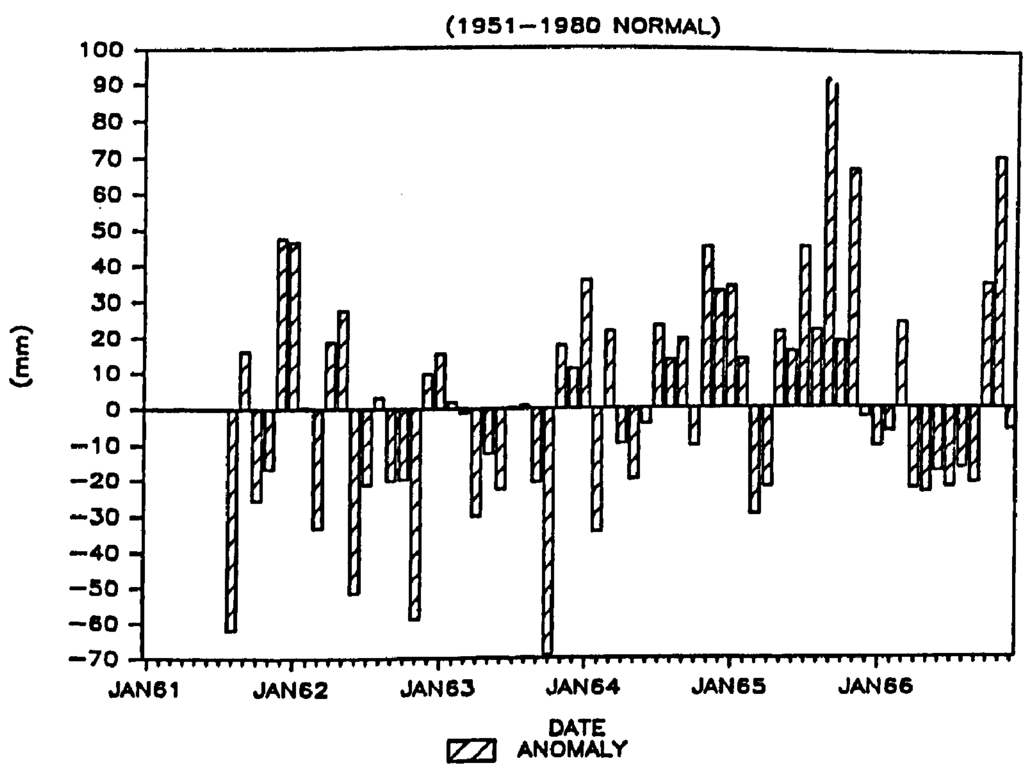

Figure 9. Monthly Precipitation Anomalies, Sault Ste. Marie, 1961-1966

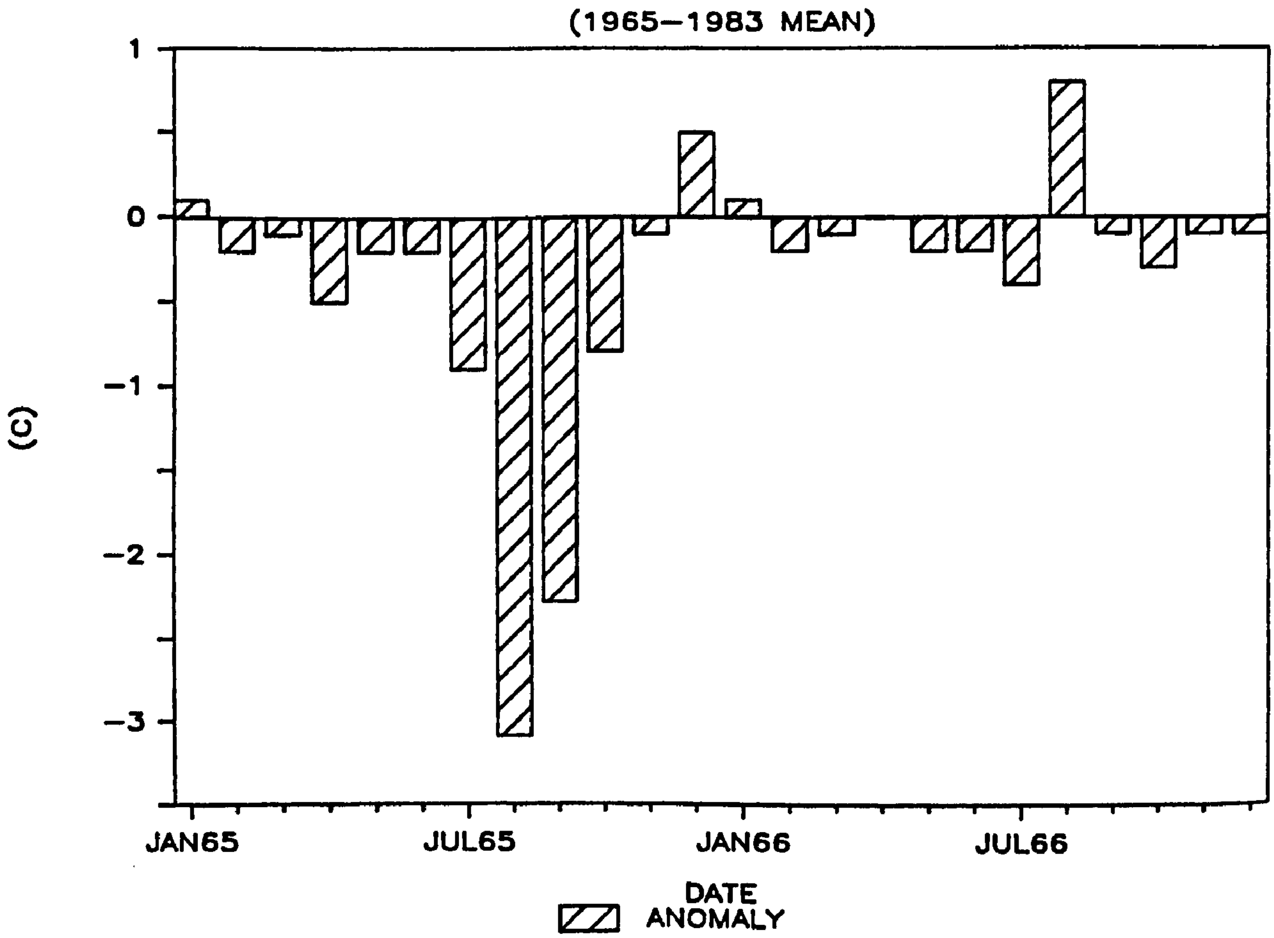

Figure 10. Monthly Lake Temperature Anomalies, Lake Superior, 1965-1966

It appears from the above information that the 1963-65 episode of low levels was initiated by below-normal precipitation in 1963. NBS returned to normal levels because of cool temperatures in 1965, and perhaps, high rainfall in the central part of the region. The cooler conditions would have reduced evaporation losses. For example, in 1965, Lake Superior evaporation was 38 mm (7%) below the 1965-84 normal.

Future Research Needs

A workshop on climate impact assessment in the Great Lakes, sponsored by the Canadian Climate Program, was held in February 1985 (Timmerman and Grima 1985). Recommendations for future research included the following:

- More direct measurements and better estimates of P(lake), E(lake), ice cover, and overland runoff
- More research on thermal structure of the lakes and of air-lake interactions
- Establishment of a regional climate monitoring system

- Research on air and water quality, including pollution from overland runoff, atmospheric deposition, and release of toxic chemicals from the lakes to the atmosphere.

Although the use of climate change scenarios from GCMs was endorsed for climate impact research in the Great Lakes, it was recommended that such scenarios be used with caution because of deficiencies in simulating boundary layer processes on a regional scale grid, which is smaller than the GCM grids. Projections of frequencies of synoptic types (e.g., dry spells) are also needed. However, this is a rapidly changing field of research and, hopefully, we may be able to see regional scenarios from GCMs in the near future.

IMPACTS

Status Report

The Great Lakes basin is a highly industralized international basin; a major producer of hydroelectric power, crops, and wood products; and an important transportation corridor. Some of these activities are directly tied to the lakes themselves (Figure 11). Others, such as winter recreation, are not dependent on the lakes directly, but might experience major impacts because of changes in climate over the land portions of the region. In addition, certain activities, such as agriculture, may experience increases in demand for water, which could lead to further declines in lake levels. Such demand could originate from outside the basin, thereby making diversion an important issue of the future, just as it is under present conditions of high lake levels.

A pilot study on impacts of CO_2-induced climatic change on Ontario was recently completed. It was coordinated by the Ontario Region of the Atmospheric Environment Service (AES), under sponsorship of the Canadian Climate Program. Participants included academics, government scientists, and private consultants. The pilot study, which used the GISS scenario, examined climate system components and resource uses (Table 2). Upon completion of the individual sector studies, a workshop was held in November 1985 to qualitatively evaluate interdependencies, identify possible mitigation strategies, and provide recommendations for future research.

A number of assessments of climate system components were presented (Table 3). The decline in NBS calculated by Inland Waters Directorate (IWD) is similar (but not identical) to results presented earlier in this discussion, although the modeling techniques were different (Shiomi 1985). Deterioration in water quality is anticipated because of higher lake temperatures. Closed marshes may dry out, while open marshes would migrate to the new lake levels. Significant decreases in snowfall and snow cover season were projected by Crowe (1985). Deterioration of air quality is anticipated because of increased intrusions of air masses from the United States (Wilson 1985). Note that most of the above judgements are qualitative, with the exception of NBS, lake levels, snowfall, and solar energy.

Impacts on resource uses are listed in Table 4. Some of these impacts are indirectly caused by climatic change, in that the change in NBS and lake levels are the causal factors. In some cases, impacts were quantitatively

GREAT LAKES IMPACTS STUDY

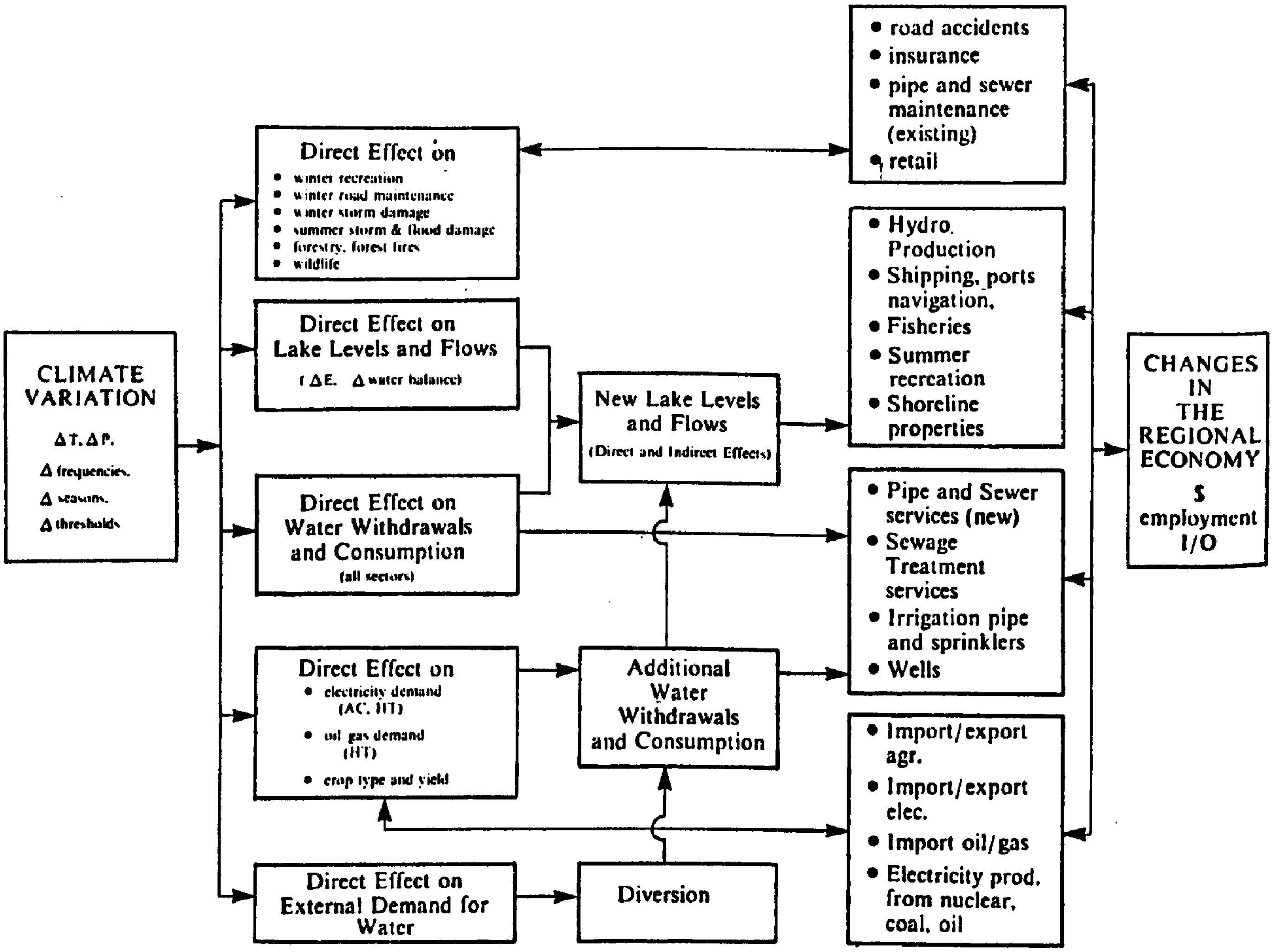

Figure 11. Interconnected components of climate impacts and societal responses within the Great Lakes region. Δ = change, T = temperature, P = precipitation, E = evaporation, AC = air conditioning, HT = space heating, I/O = inputs/outputs (Cohen 1986a).

Table 2. List of Individual Sector Studies

TOPIC	QUANT/QUAL	$	PARTICIPANT*
CLIMATE SYSTEM			
Streamflow Net Basin Supply Lake Levels	QUANT		IWD (with AES)
Water Quality	QUAL		IWD
Wetlands	QUAL		Wall et al.
Snowfall	QUANT		AES
Air Quality	QUAL		AES
Solar Energy	QUANT		AES
RESOURCE USE			
Electricity Demand	QUANT	$	U. of Windsor
HT and AC Demand	QUANT		AES
Hydroelectric Power	QUANT	$	U. of Windsor
Shipping	QUANT	$	U. of Windsor
Agriculture	QUANT	$	U. of Guelph
Tourism & Recreation	QUANT	$	Wall et al.
Municipal Water Use	QUANT		AES
Forestry	QUAL		CFS
Health	QUAL		workshop

* AES = Atmospheric Environment Service
CFS = Canadian Forestry Service
IWD = Inland Waters Directorate

Table 3. Impacts of GISS Scenario of CO_2-Induced Climatic Change on Climate System Components in Ontario

CLIMATE SYSTEM COMPONENT	IMPACT
Net Basin Supply Cohen 1986a)	-15.3% overall (-20.8% in
-23.8% with consumptive use (-28.9% in Cohen 1986b)	
Lake Levels Mich-Hur: -0.59 m/-0.83 m Erie: -0.44 m/-0.68 m Ontario: (N/A)	Superior: -0.22 m/-0.30 m
Ice Cover	reduced to zero (Erie?)
Snowfall	-80 to 140 cm (Crowe)
Snow Cover	-4 to 6 weeks (Crowe)
-6 to 10 weeks (Wall et al.)	
Solar Energy	little change
Water Quality	less dilution
Air Quality	reduced cold season pollution and acid shock
	increased intrusion of polluted air masses northward
	increased wet deposition
	increased local and regional episodes

Table 4. Impacts of CO_2-Induced Climatic Change on the Economy of Ontario (Allsopp and Cohen 1986)

RESOURCE USE	IMPACT	ANNUAL GAIN/LOSS ($ MILLION CDN)
Electricity Demand (U. of Windsor 1986)	Reduced winter space heating demand=6533 to 7840 GWh. Increased summer air cond. demand=162 to 216 GWh. Net reduction=6371 to 7624 GWh.	+99 to +118 (reduced costs to provincial utility)
Res. Heating and Cooling Demand (Bhartendu and Cohen 1986)	Reduced space heating demand= -45%. Increased summer cooling demand= +7%.	+?
Hydroelectric Power (U. of Windsor 1986)	Reductions due to lower lake levels and flows, except at St. Mary's River. Losses at De Cew, Sir Adam Beck, and Robert H. Saunders power plants. Total loss=2220 to 4165 GWh, depending on Lake Ontario regulation.	-34 to -65
Great Lakes Shipping (U. of Windsor 1986)	Reduced cargo per vessel due to lower channel depths. Losses are highest if coal shipments greater than present. Losses do not include delays at canal locks due to potentially heavier traffic and occur despite reduction of ice cover and longer shipping season.	-10 to -27 ($US)
Agriculture (U. of Guelph 1985)	Reductions in crop yield due to increased heat and moisture stress; below potential crop yield due to technological improvements. This considers positive impacts of extended growing season and northern expansion, but does not consider new crops or irrigation.	-107

Table 4. Cont.

RESOURCE USE	IMPACT	ANNUAL GAIN/LOSS ($ MILLION CDN)
Tourism and Recreation (Wall et al. 1985)	Greater use of parks and campgrounds due to longer summer and shoulder seasons. Indirect gains would occur in local retail sectors. Eight parks were studied.	+4
	Ski areas in southern Ontario could be eliminated due to reduction in snow season. Small loss or gain could occur in the north, depending on success of competing facilities elsewhere (e.g., Laurentians) local retail sectors (e.g., Collingwood).	-50
	Effects of changes in lake levels, streamflow, and water quality on shoreline properties and wetlands. Possible negative impacts on closed marsh.	?
Municipal Water Use (Cohen 1985)	Increased demand of 5 litres per capital per day during May-September, due to warmer summer season. This may also result in increased demand for treatment services, and accelerate the expansion of surface water distribution systems, and replacement of wells in some areas.	-?
Forestry (Stocks 1985)	During the transition from boreal forest to new hardwood forest types, there would be increased damage due to disease, insects, and fire, and reduction in winter logging operations. Possible benefits could result from CO_2 enrichment.	-?
Health, Air, and Water Quality	Increase in heat stress. Decrease in cold stress. Poorer air and water quality in summer?	?

estimated, so these results are presented where available. Impacts are largely negative, particularly in agriculture, winter recreation, and hydroelectric power production.

However, reductions in energy demand represent a significant saving. The lower electricity demand actually overshadows the loss in hydroelectric power production. More research is needed to determine the economic effects of reduced demand for heating oil and natural gas, as well as increased demand for summer air conditioning. The latter may be underestimated because it is based on a weak correlation with temperature, and does not include extreme events. Although per household energy consumption should decline, population growth should still lead to an increase in total demand by the mid-21st century.

Some of these results require additional discussion. The loss projected for agriculture represents the effect of CO_2-induced climate change on future crop yields with future technology. Technological change is expected to increase yields by 66% between 1981 and the mid-21st century. The GISS scenario would reduce this gain to 60%. That 6% loss in anticipated yield is equivalent to $107 million (Canadian) in 1981 dollars. If precipitation was higher than the GISS scenario, yields would increase further. Lower precipitation could lead to yield decreases below present production due to moisture stress. Overall, it is projected that many areas in southern Ontario would not be able to support grain corn, particularly soils that are well drained or prone to droughtiness. Some of this stress could be alleviated by irrigation, so the availability of irrigation water will become more important in the future than it is at present.

Water use by municipalities will also be influenced by CO_2-induced climate change. Results were based on regression models for 17 cities in the region. The study only considered changes in summer temperatures and did not include possible feedbacks due to future increases in demand for piped surface water by agriculture, recreation facilities, and other users of groundwater. The increased demand is considered a loss, since costs to municipalities would probably increase, and under present pricing arrangements, such costs would not be completely met by revenues collected from consumers.

Forest resources would undergo a transition from boreal to mostly hardwood species. During the transition, damage to the existing boreal forest by disease, insects, and forest fires would increase. Reductions in snow and ice cover may reduce damage to mature trees, but could increase desiccation of seedlings, affect life cycles of insects and animals, introduce an earlier forest fire season, and interfere or constrain winter logging operations dependent on snow cover or frozen ground.

In summary, a wide range of topics has been considered, but a great deal of work remains to be done, particularly in areas where no quantitative modeling has been attempted, such as air and water quality changes, and their subsequent impacts on resource uses. We will return to this in the Future Research Needs section.

During the November 1985 workshop, three types of strategies were considered that could mitigate the consequences of climatic change: preventive, compensatory, and substitutional.

Preventive strategies include removal of CO_2 from emissions. Since this is a global problem, it was felt that any action here would have little effect, though it might encourage other jurisdictions to follow suit. Compensatory strategies involve altering resources to meet human needs (e.g., dredging to avoid draft restrictions for commercial shipping), and a number of these are listed in Table 5. Substitutional strategies focus on adapting human needs to the "changed" resource (e.g., new ship design for shallower draft). These are also included in Table 5. This list was selected from a longer list of possibilities. No quantitative modeling has been done to evaluate the effectiveness of these strategies, and this too will be discussed in the following section.

Future Research Needs

As indicated in the previous discussion, a number of important topics require further study. For atmospheric scientists and hydrologists, these include incorporation of regional scale processes (e.g., lake effect snowfall) into GCMs and projections of synoptic type frequencies (e.g., frequencies of dry spells) in a "greenhouse effect" climate. The present data base could be improved if there were regular direct measurements over the lake surface of air temperature, water temperature, wind speed, relative humidity, and precipitation. All these data are needed to improve estimates of projected lake evaporation, NBS, air quality, and frequencies of extreme events.

A wide range of quantitative impacts studies are still needed to provide a more complete picture of biophysical and socioeconomic effects. Priority areas appear to be health, air quality, water quality, forest growth (including pests and disease), forest fires, wetlands, fisheries, land transportation, water consumption during dry periods, and air conditioning demand. Additional work is needed to determine secondary economic effects that might result from changes in agriculture, outdoor recreation, lake shipping, space heating demand, and hydroelectric power production. An analogue study of the 1963-65 period may be of benefit in identifying ripple/multiplier effects of low lake levels on various aspects of the region's economy, such as real estate values, changes in water prices, insurance, and recreation activities in wetlands and shoreline areas.

A number of mitigation strategies were considered in the previous section. The decision to implement any or all of these requires additional research on their feasibility, costs, benefits, and possible side effects. Since many of these have political implications, it is better to perform cost/benefit and other kinds of analyses as early as possible, so that the issues can be discussed in public before action is needed.

Table 5. Strategies for Mitigation of Impacts of CO_2-Induced Climatic Change in Ontario

RESOURCE USE	COMPENSATORY STRATEGIES	SUBSTITUTIONAL STRATEGIES
Residential Heating and Cooling		New Technology
Great Lakes Shipping	Regulate Lake Levels Extend Season	Redesign Ships
Hydroelectric	Use Available Water	Modern Technology--Retrofit Conservation Other Energy Sources
Agriculture	Irrigation	Northern Extension
Tourism and Recreation		Diversify Operations and Activities
Municipal Water Use		Conservation Technology
Forest Resources	Shorter Rotation Intensive Management Genetic Adaptation	Reforestation
Health, Air, and Water Quality	Improve Water Treatment Reduce Contaminants	

CONCLUSION

Recent efforts in climate impacts research has led to increased awareness of climate-environment and climate-society interactions. There have been more questions than answers, and researchers have been extremely cautious about discussing results because of the numerous uncertainties about CO_2-induced climate change, future technological change, and the various modeling procedures employed in the research. Some have said that impacts research is premature, and that we should wait until these uncertainties are resolved. However, it will take considerable effort to develop improved methods and models. Impacts research conducted today will better prepare us as researchers to assess these impacts when climate modeling reaches a more advanced stage of development.

ACKNOWLEDGMENTS

My sincere thanks to G. Irbe for providing the data on lake evaporation calculated from and based stations.

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Climatic Evolution and Variability in Dryland Regions: Applications of History to Future Climatic Change

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Climate is an environmental factor that has influenced the course of human activities throughout history. It is also a highly variable characteristic of the human environment. Dramatic changes, such as the Ice Ages, have occurred on geological time scales; less extreme but nevertheless significant fluctuations have occurred during recent centuries. In the past, climatic change resulted from "natural" (i.e., geophysical factors) such as volcanic activity, ocean-atmosphere feedback, or changing patterns of solar irradiance. Now a wealth of evidence suggests that mankind's impact on the atmosphere rivals natural effects, and such factors as increased carbon dioxide or atmospheric trace gases may produce changes of a magnitude unequaled during recent history.

If the projected changes occur--notably a global warming--it is the climatic transition zones, such as the polar margins or the semi-arid regions, that will undergo the greatest climate changes. In the high latitude margins, temperature is the most critical variable, but in the semi-arid lands, water is the limiting factor, and the changing water resource issue has the greatest impact in these regions. This paper summarizes the history of rainfall changes in dryland regions to provide a basis for assessing the magnitude of climatic changes that might be expected from human impact on the atmospheric system.

In some parts of the world, knowledge of past weather and climate is readily derived from written records and from other methodologies, such as tree-ring analysis. In Europe, for example, instrumental records go back three centuries and detailed information for early times can be derived from historical archives, weather chronicles, records of river flows and freezing dates, wine harvests, and a variety of other indicators providing local information both seasonally and annually. In many dryland regions, especially those in developing countries, information is scarce and few long-term or

Table 1. Types of Data Useful for Historical Climatic Reconstructions, Particularly with Respect to Africa

I Landscape descriptions

1 Forests and vegetation: are they as today?
2 Conditions of lakes and rivers:
  (*a*) height of the annual flood, month of maximum flow of the river
  (*b*) villages directly along lakeshores
  (*c*) size of the lake (e.g. as indicated on map)
  (*d*) navigability of rivers
  (*e*) desiccation of present-day lakes or appearance of lakes no longer existing
  (*f*) floods
  (*g*) seasonality of flow; condition in wet and dry seasons
3 Wells, oases, bogs in presently dry areas
4 Flow of wadis
5 Measured height of lake surfaces (frequently given in travel journals, but optimally some instrumental calibration or standard should accompany this)

II Drought, famine and other agricultural information

1 References to famine or drought, preferably accompanied by the following:
  (*a*) where occurred and when occurred: as precisely as possible
  (*b*) who reported it; whether the information is second hand
  (*c*) severity of the famine or drought; local or widespread?
  (*d*) cause of the famine
2 Agricultural prosperity:
  (*a*) condition of harvest
  (*b*) what produced this condition
  (*c*) months of harvests, in both bad years and good years
  (*d*) what crops grown
3 Wet cultivation in regions presently too arid

III Climate and meteorology

1 Measurements of temperature, rainfall, etc.
2 Weather diaries
3. Descriptions of climate and the rainy season: when do the rains occur, what winds prevail?
4 References to occurrence of rain, tornado, storm
5 Seasonality and frequency of tornadoes, storms
6 Snowfalls: is this clearly snow or may the reporter be mistakenly reporting frost, etc?
7 Freezing temperatures, frost, hail
8 Duration of snow cover on mountains (or absence)
9 References to dry or wet years, severe or mild winters, other unusual seasons

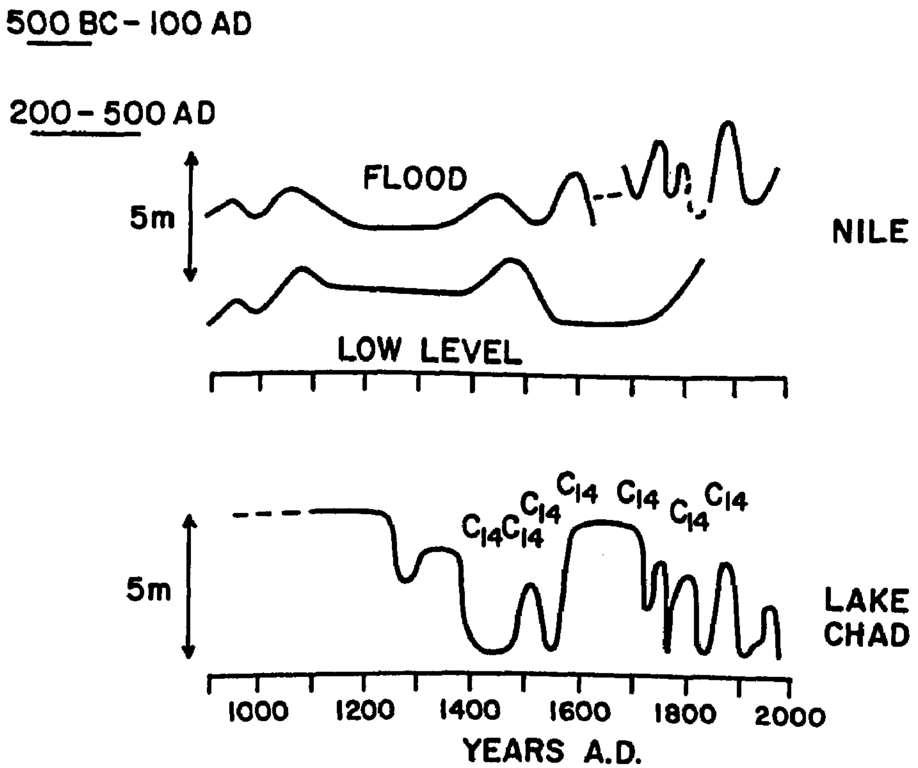


Figure 1. Fluctuations of Lake Chad and the Nile in Historical Times (Maley 1981; Nicholson 1976)

quantitative records exist. The principal indicators of weather and climate (Table 1) that are useful in dryland regions include landscape descriptions (vegetation and water bodies); drought, flood, and harvest information; and climate and weather descriptions (Figure 1). Typical sources are settlers' diaries, archives, travellers' and explorers' journals, geographical texts, maps, written and oral histories and local chronicles. When carefully assessed, these sources provide rough estimates of rainfall fluctuations that have occurred in recent centuries. Although, with the exception of lake-levels or river flow, this is not a direct assessment of changes in the water balance or of available water resources, some general inferences can be made (Nicholson 1979).

Figure 2 illustrates long-term fluctuations in the sub-Saharan regions of Africa (i.e., the Sahel and neighboring regions); these are generally paralleled by fluctuations along the northern margin of the Sahara (Nicholson 1976, 1978, 1979, 1980). For southern Africa, less long-term information is available but as of about 1700, the evidence suggests that fluctuations in the dryland regions of southern Africa more or less paralleled those south of the Sahara (Nicholson 1981). Wetter conditions prevailed during the last few centuries B.C. and into the first century of the Christian era. A second humid episode occurred during the ninth through thirteenth centuries. More recent fluctuations were of lower magnitude and included wetter conditions in the sixteenth through eighteenth centuries and again in the late nineteenth century (c. 1870-95) and long and severe droughts during the 1820s and 1830s (Figures 3, 4, and 5). Long intense droughts in the Sahel also occurred in the 1680s and c. 1738-56. Throughout most of Africa, the present century has been relatively dry compared with the historical past.

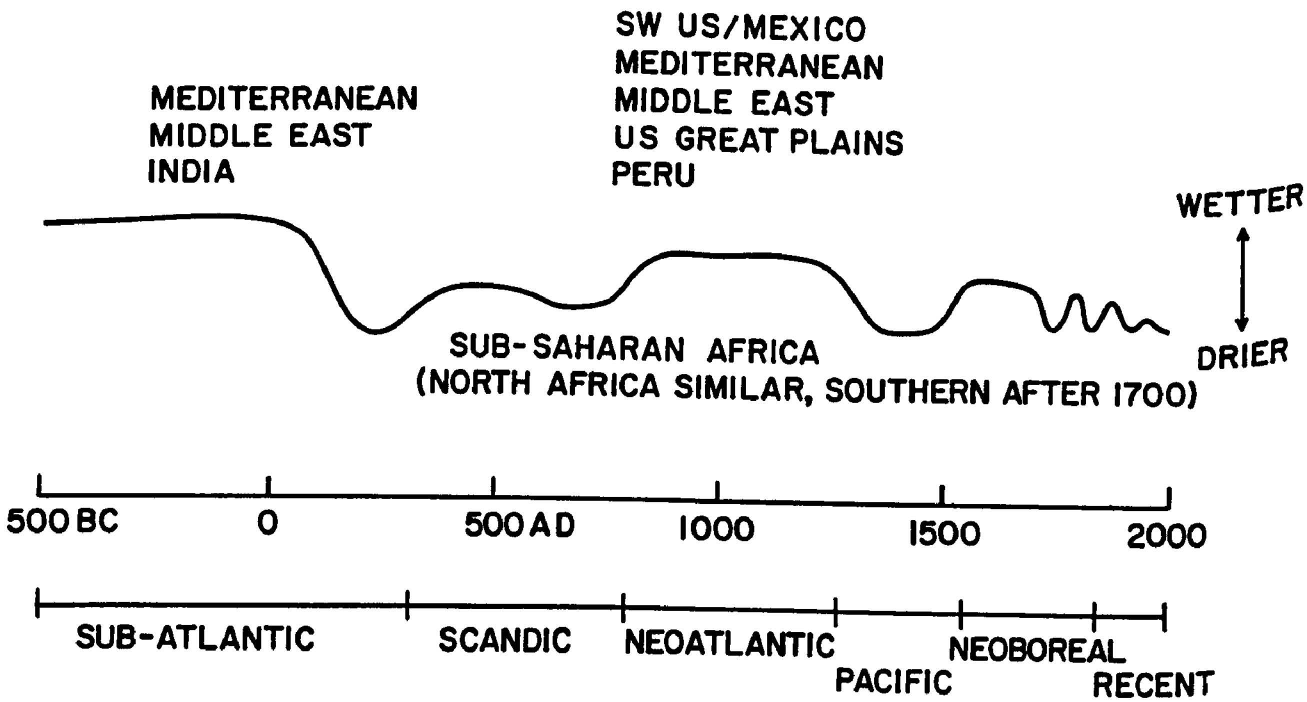


Figure 2. Long-term rainfall fluctuations in sub-Saharan Africa (i.e., the Sahel) and other regions, compared with global climatic episodes (see Table 2). Northern Africa broadly parallels the Sahel, as do the semi-arid regions of southern Africa after c. 1700. Other locations with wetter conditions during sub-Atlantic and Neo-Atlantic times are listed above the curves.

The fluctuations described for the sub-Saharan region appear to be relatively synchronous with the major episodes of climate recognized first from pollen sequences and later from radiocarbon dating of indicators of environmental changes (Wendland and Bryson 1974). These episodes and their approximate timing are indicated in Table 2. The humid episode south of the Sahara that ended at the beginning of the Christian era roughly corresponds to the Sub-Atlantic period. The second humid episode corresponds to the Neo-Atlantic, a period of warmer conditions over much of the northern hemisphere during medieval times. The most recent extended period of more humid conditions in the sub-Saharan region occurred during the Neo-boreal, a period also called the "Little Ice Age." It is known that the episodes in Table 2 are probably hemispheric and perhaps even global fluctuations, thus the general correspondence with sub-Saharan rainfall fluctuations is not surprising. Similar fluctuations probably occurred in other dryland regions, but extensive historical material has only been collected and synthesized into a climatic chronology for the United States.

Table 2. Approximate Dates of Global Climatic Episodes
Source: Wendland and Bryson 1974

EPISODE	DATE
SUB-ATLANTIC	500 B.C. - 300 A.D.
SCANDIC	300 A.D. - 800 A.D.
NEO-ATLANTIC	800 A.D. - 1250 A.D.
PACIFIC	1200 A.D. - 1550 A.D.
NEOBOREAL	1550 A.D. - 1850 A.D.
RECENT	1850 A.D. to present

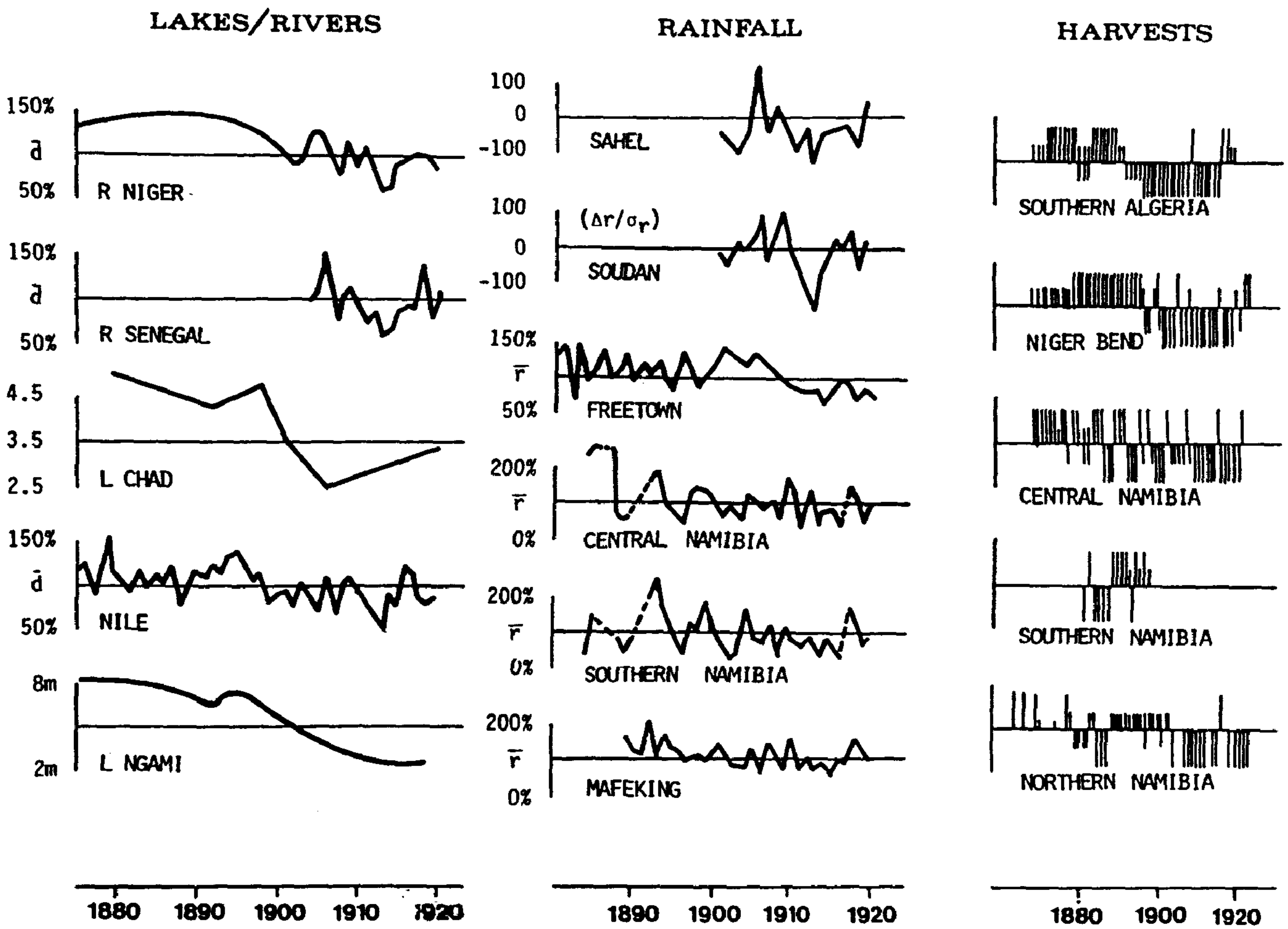


Figure 3. Trends of African Climate Indicators (Rainfall, Rivers, Lakes, Harvests), 1880 to 1920. Harvest quality, good = above the axis, poor = below the axis; rainfall r and river discharge d expressed as % of the mean (r or d) or % of standard departure; lake levels, annual mean surface height, in meters (from Nicholson 1978).

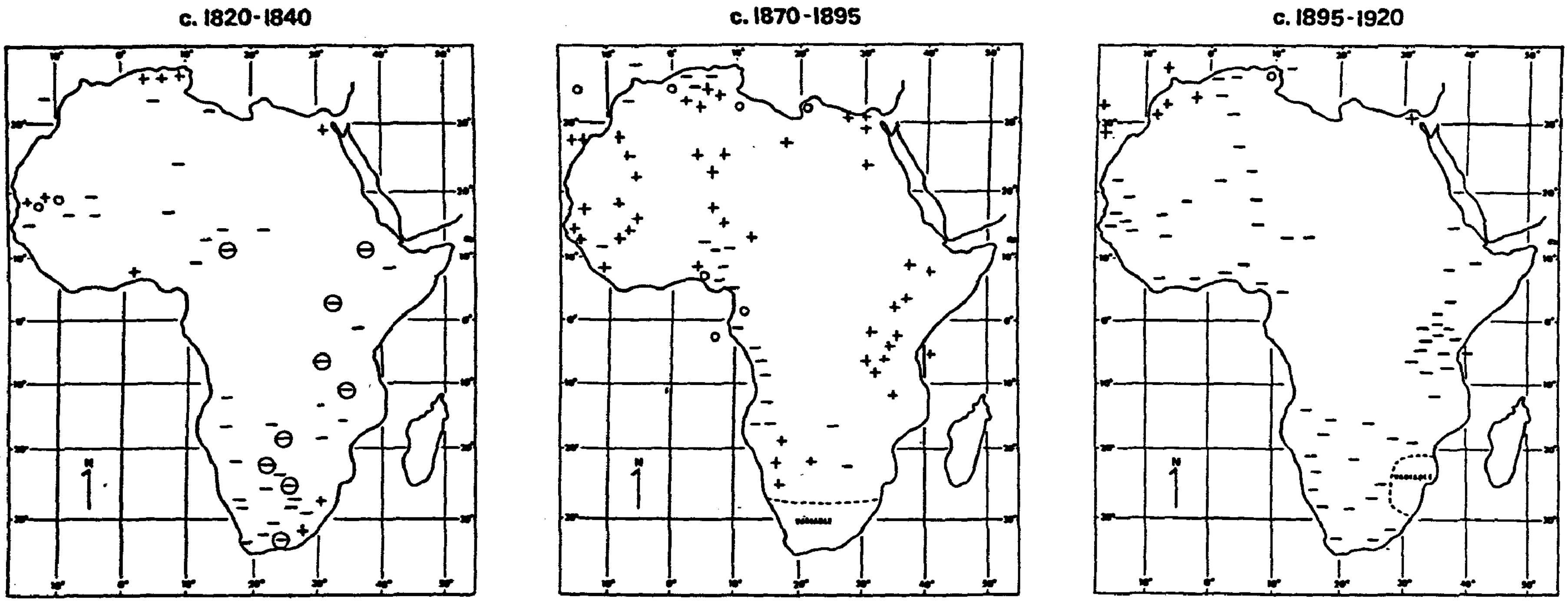


Figure 4. African Rainfall for the Periods 1820 to 1840, 1870 to 1895, and 1895 to 1920.
(+ is above normal, 0 is normal, - is below normal)
Source: Various historical materials (Nicholson 1978).

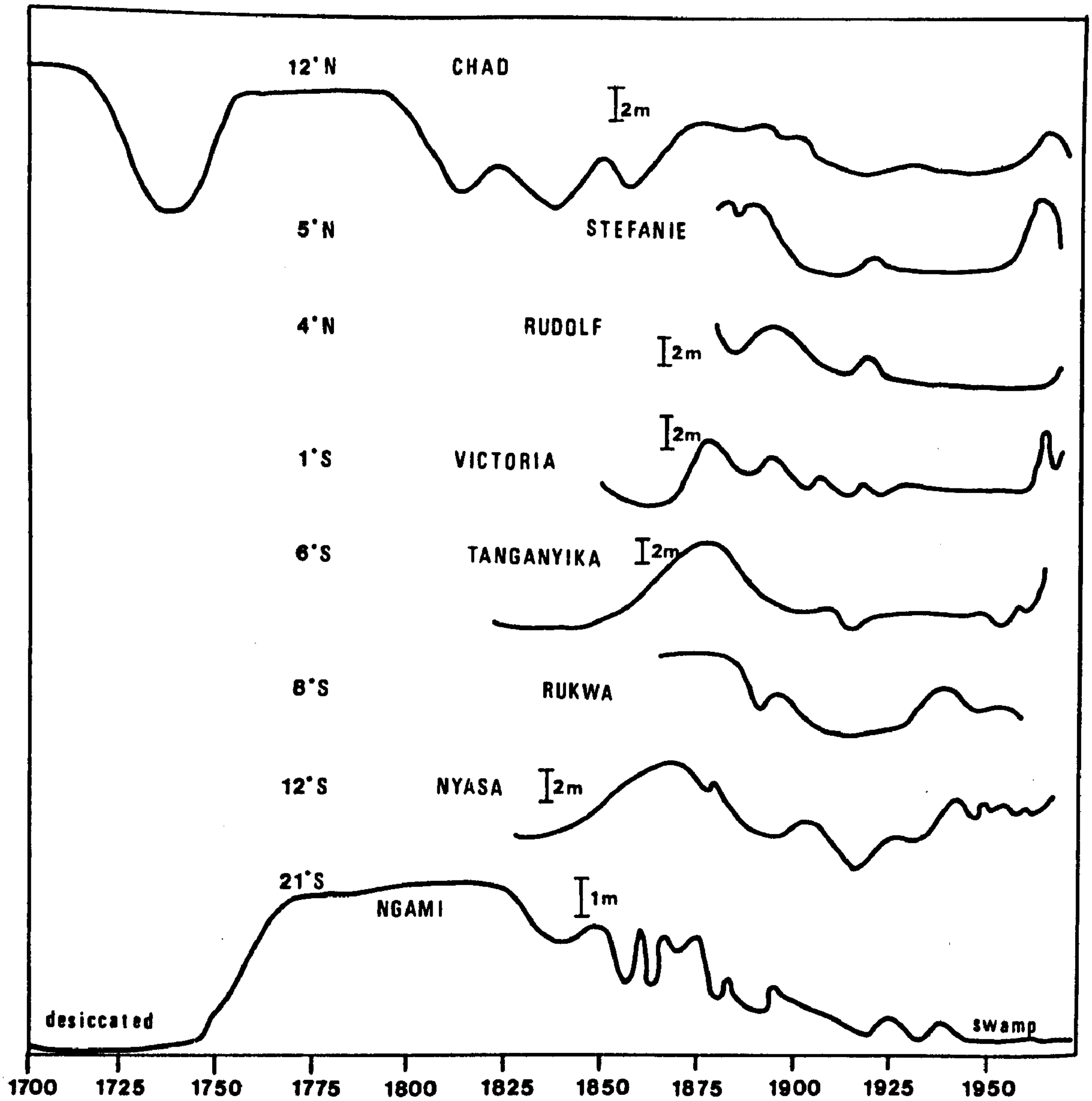


Figure 5. Variation of African Lake Levels Since 1700 (Nicholson 1978)

The remainder of this paper will provide a brief sketch of general trends in dryland regions of the United States, South America, India, Asia, and Australia. Note, however, that the remaining discussion is usually based on a few indicators or investigations for each region in contrast to the chronology for Africa, which was derived from several years of research using literally hundreds of sources. Thus, the following descriptions of historical climate fluctuations in other dryland regions should be viewed as merely sketchy summaries of a few readily available documents; the fluctuations described must be verified by extensive research and compilation of much more evidence.

The two major dryland regions of the United States include the Great Plains and the deserts of the Southwest. Detailed knowledge of the last 400 years (Figure 6) is derived from tree-ring analysis (Stockton and Meko 1983); archaeological studies and a few tree-ring series provide information for much longer periods (Lamb 1977). The settlements and the pollen record from Mill Creek, Iowa (Bryson and Baerrais 1965) suggest that relatively wet conditions prevailed in the Great Plains from c. 700 to 1200 A.D. (Table 3). The people of the region were farmers inhabiting a land with dense stands of trees, forest animals such as deer, and tall grass prairies. Within a few decades, drier conditions set in and lasted until c. 1400. The settlements were abandoned, the prairies and woodlands gave way to short-grass steppe, and the dominant animal herds were plains animals, such as bison. Tree-rings suggest wetter conditions again prevailed c. 1400 to 1650, but relatively dry conditions characterized the period c. 1650 to 1900. The present century is comparatively wet but probably also warmer than the few centuries prior to it. Similar fluctuations occurred in the arid Southwest and Great Basin and probably in Mexico (Lamb 1977, 1982; Leopold, Leopold, and Wendorf 1961; McGhee 1981).

For most other dry regions of the world, much less information is available for the longer time period. In Peru, Ecuador, and the Galapagos Islands (Table 4) some archaeological evidence exists of dry conditions c. 600 to 1000 A.D., wetter ones c. 1000 to 1400, then drier conditions until c. 1650. The dry conditions c. 1500-1650 are also suggested by an analysis of ships' logs, diaries, and other historical information. This material also indicates wetter conditions c. 1650 to 1850, and conditions similar to the present ones commencing c. 1850. Not enough material is available to generalize climatic fluctuations beyond a century or two for other regions. In Arabia, the Mediterranean, and the Middle East, rainfall fluctuations probably paralleled those for sub-Saharan Africa (Figure 2) (Lamb 1977, 1982; Rosenan 1963; McGhee 1981). Only scanty evidence in the form of lake level fluctuations (Figure 7) and dunes is available for the U.S.S.R. and Central Asia, as well as one very general drought chronology for the Ukraine. For the desert regions of India and China, little information is available in western literature although presumably, given the long historical traditions in both countries and the very early interest in meteorology in both, extensive information could probably be found.

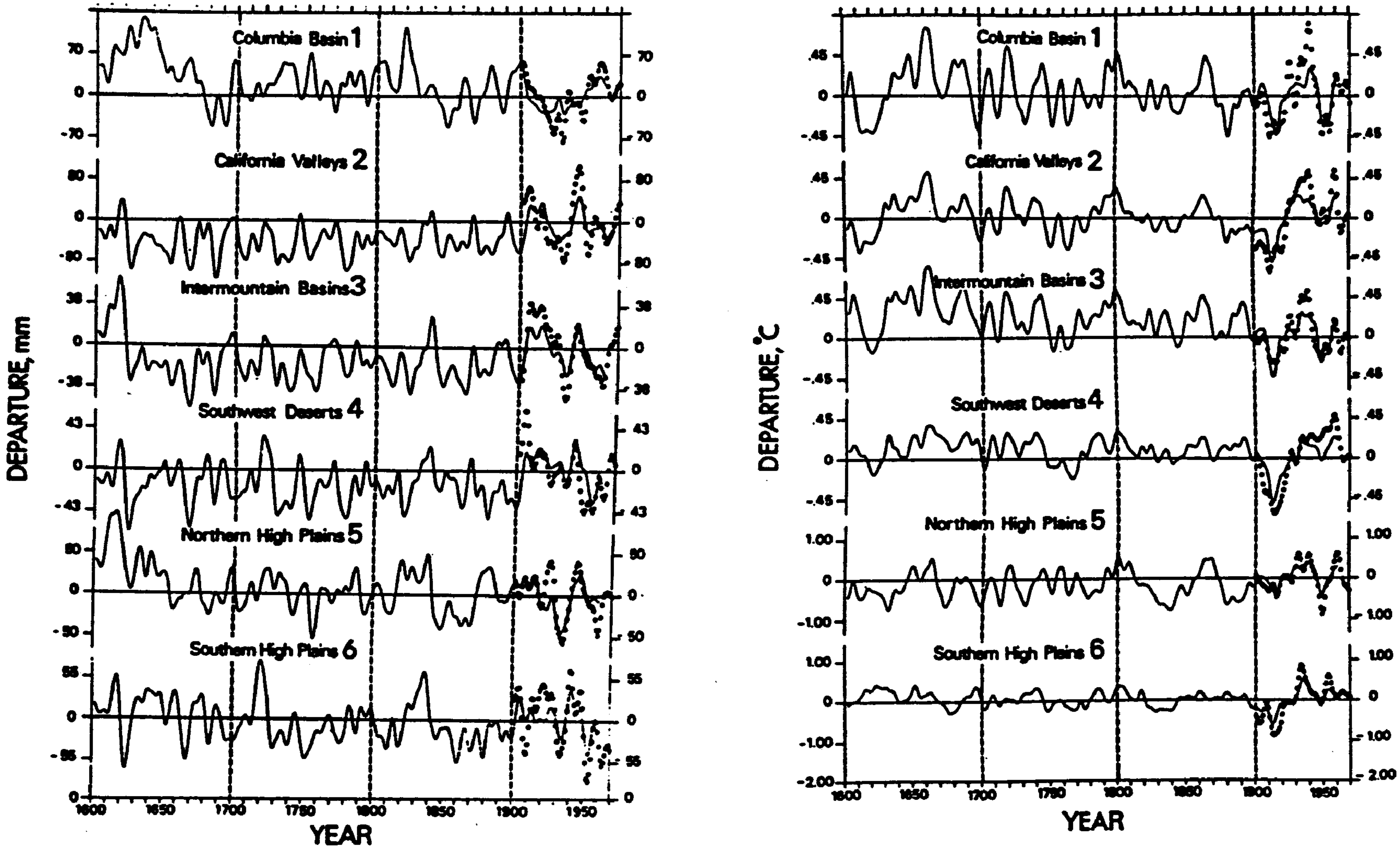


Figure 6. Regionalized Annual Temperature and Rainfall Reconstructions for Six Regions of the Western United States, Based on Tree Ring Analysis (dots on right indicate instrumental data). Source: Fritts et al., unpublished manuscript).

Table 3. Long-term Climatic Fluctuations in the Dryland Regions of the United States (see Bryson and Baerrais 1968; Lamb 1977, 1982; McGhee 1981; Leopold et al. 1963; Fritts et al. 1982; Stockton and Meko 1983).

U.S. GREAT PLAINS		
c. 700 - 1200 A.D.	WETTER	
		Settlements at Mill Creek Farming Trees, tall grass prairie, deer
c. 1200 - 1400	DRIER	Mill Creek settlements abandoned Decrease in oak and other tree pollen Increase in bison herds - plains animals Short-grass steppe
c. 1400 - 1650	WETTER	
c. 1650 - 1900	DRIER	(except c. 1720-30, c. 1820-40)
U.S. SOUTHWEST/GREAT BASIN/CALIFORNIA VALLEYS		
c. 500 - 600 A.D.	ONSET OF DRIER CONDITIONS	
c. 800 - 1100 A.D.	PROBABLY WETTER	
		Erosion instead of sedimentation Dry farming
c. 1100 - 1300 A.D.	DRYING	Irrigation replaces dry farming Settlements abandoned Tree rings
c. 1620 - 1900 A.D.	DRIER THAN PRESENT	

Table 4. Long-term Climatic Fluctuations in Peru, Ecuador, and the Galapagos Islands (see Pejml 1966; McGhee 1981; Lamb 1977, 1982).

c. 600 - 1000	DRY (Ecuador coast)
c. 1000 - 1400	WET (Ecuador coast)
	(Wells in use, agriculture)
c. 1400	ONSET OF DRIER CONDITIONS
c. 1500	LAKE TITICACA FELL SEVERAL METERS
c. 1500 - 1650	DRY
c. 1650 - 1850	WET (Ships' logs, lakes, diaries)
c. 1850 to now	DRY

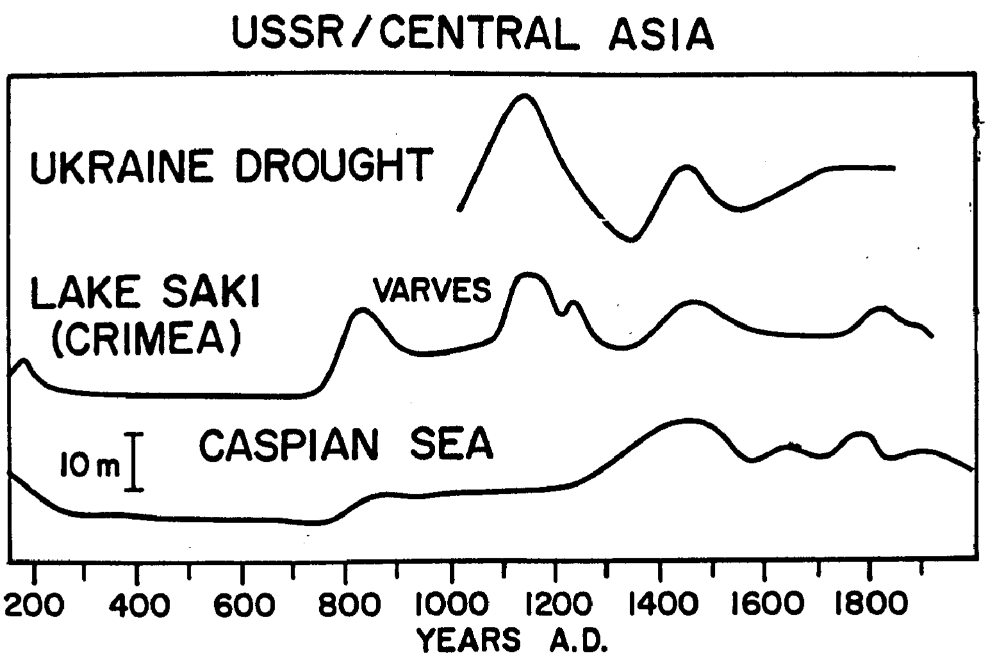


Figure 7. Variations of Asian Lakes Compared with a Drought Index for the Ukraine
Source: Lamb 1982, 1977; Buchinsky 1963

At first glance, the coincidence of wetter episodes in approximately the nineth through thirteenth centuries in Africa, the U.S. Great Plains and arid southwest, and Peru suggests some broad synchroneity in rainfall fluctuations in the earth's dryland regions. A more detailed look at recent centuries suggests, however, that this is not the case. Figure 8 summarizes rainfall fluctuations and drought from c. 1750 to the present for central Chile, the U.S. Great Plains, Peru, and India. Very few generalizations can be drawn for all four regions. Some periods do, however, stand out. In the 1820s and 1830s (a period of continental drought in Africa), rainfall conditions in central Chile were generally good while in the drier regions of the U.S. that period tended to be both cold and wet (Figures 6 and 8).

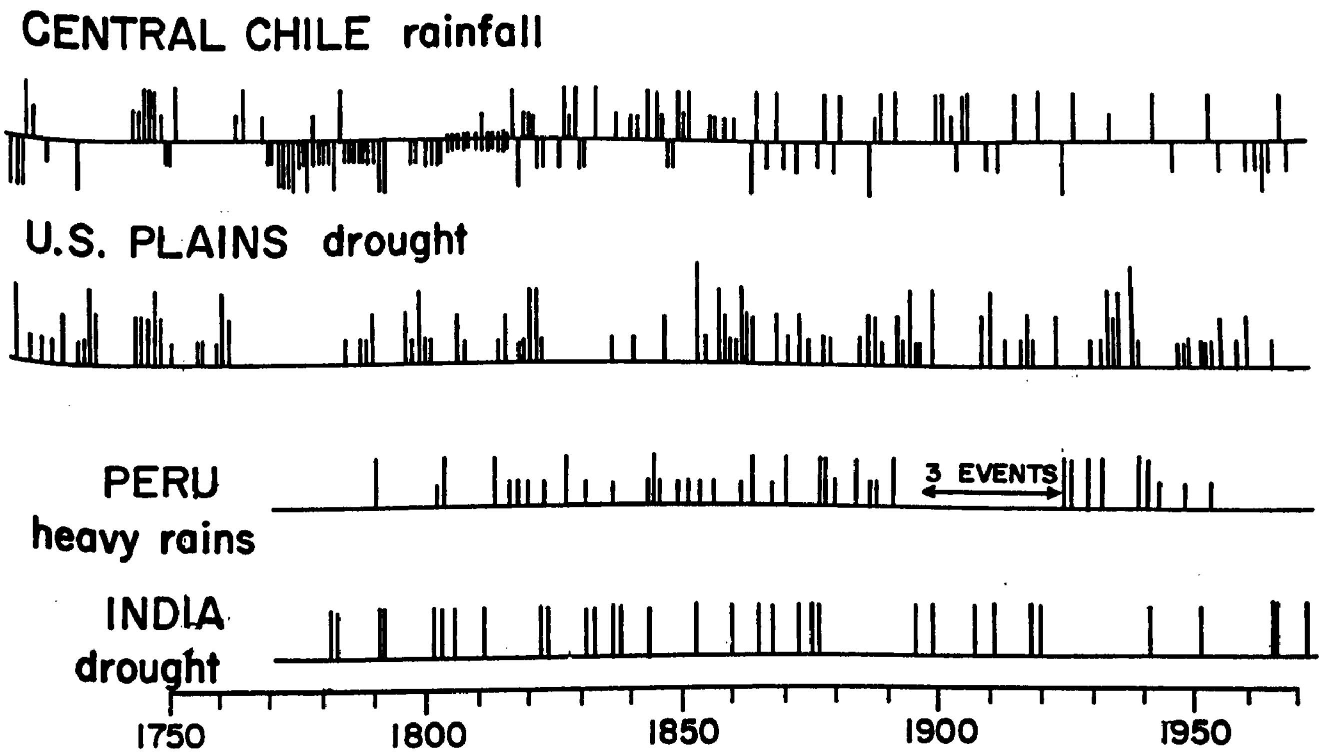


Figure 8. Rainfall fluctuations and drought occurrences in Central Chile, Peru, the United States, Great Plains and India (U.S. drought, length of marker indicates drought severity; India, drought years indicated; Peru, markers indicate occurrences of heavy rainfall, longer markers indicating particularly strong rains; Chilean rainfall, length of marker indicates relative magnitude or departures from normal).

Major fluctuations that occurred at the end of the nineteenth century can also be traced to many regions. In many of the semi-arid regions of Africa rainfall during the period c. 1870-1895 averaged 20%-30% above the mean for the present century. The situation changed very abruptly in the 1890s and rainfall decreased rapidly in many regions, a trend culminating in severe droughts in the 1910s. With the possible exception of the 1950s rainfall in semi-arid Africa was probably never again as copious as in the late nineteenth century. Kraus (1955), using data primarily from India, Australia, and the Mediterranean, observed that this trend was a general one throughout the tropics and it was also evident in parts of the United States (Wahl and Lawson 1970). Data for a few selected regions are given in Figures 9 through 14. In many cases, wetter conditions returned in mid-twentieth century.

It is difficult to draw conclusions from such sketchy material, but a few observations can be made. First, changes in water availability on a historical time scale can be documented for many dryland regions and these are often of great enough magnitude to have been highly significant for the regions' population. In Africa, for example, rainfall in areas such as the Sahel was probably 20-30% above the present mean within recent centuries, but conditions even drier than the current ones have also occurred. In semi-arid parts of the United States, similar changes in rainfall and streamflow in order of 20-30% have occurred. Some changes have occurred rather abruptly, others as a gradual trend. In notable examples, not only the magnitude of rainfall has fluctuated, but the variability in time and also the seasonal distribution have been affected. The historical fluctuations of rainfall have not been spatially uniform, even within the dryland regions. Nor is there any consistent pattern of increased or decreased rainfall in association with apparent global temperature changes. Changes in rainfall might be accompanied by changes in temperature, which also influence the water balance via evaporation. This is a more significant effect in higher latitudes and in some regions, notably the U.S. Great Plains, reduced rainfall is often associated with higher temperatures. In tropical dryland regions, both historical information and model results suggest that changes of temperature are likely to be small.

It is even more difficult to generalize about changes of rainfall or water resources that might occur as a result of human-induced climate change, such as the projected global warming due to increased carbon dioxide. Although there is fair agreement among estimates of global temperature changes, the model projections of changes in rainfall and soil moisture show little consistency in results (Figure 15). Moreover, the trends of climate in the historical past show that calculations must be regionally specific, because few trends can be generalized, and this is beyond the state-of-the-art for climate models. Another approach is to use past conditions as analogs to a global warming; the Altithermal of c. 6000 B.P. is often used as such an analog. At that time rainfall was considerably higher than at present in many low-latitude dryland regions but relatively dry in others, such as the agricultural regions of the United States (Figure 16). The suggested changes of rainfall do resemble model projects for a doubling or quadrupling of CO_2 (Figures 17 and 18), and are markedly similar to rainfall changes, as can best be established, during the warmer Neo-Atlantic period in the nineth through thirteenth centuries. Nevertheless, in many areas similar changes of rainfall also occurred during periods of globally reduced temperatures, and firm predictions cannot be made.

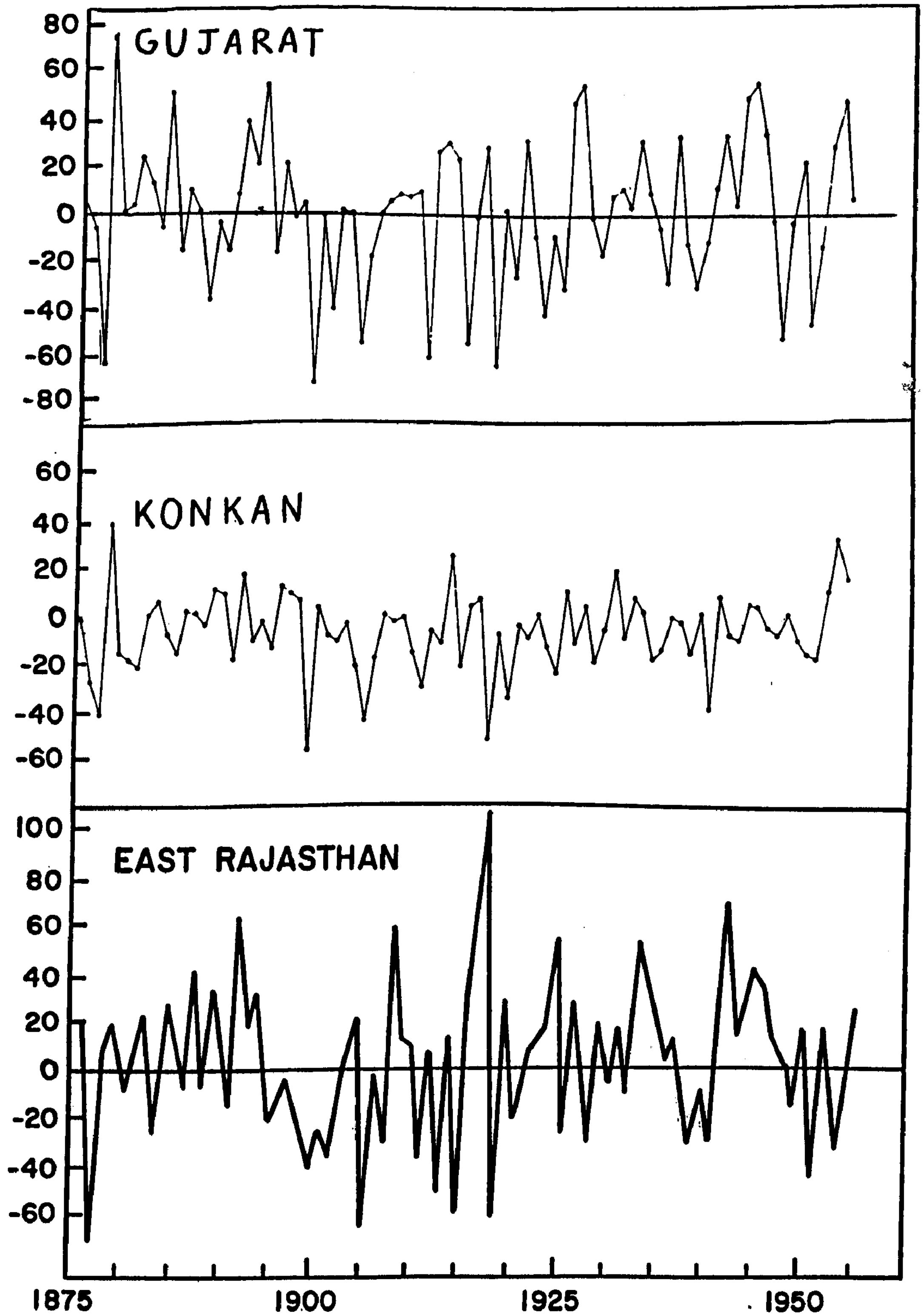


Figure 9. Fluctuations of Rainfall (% Departure from Normal) in Arid Regions of India, 1875-1955
Source: Rao and Jagannathan 1963

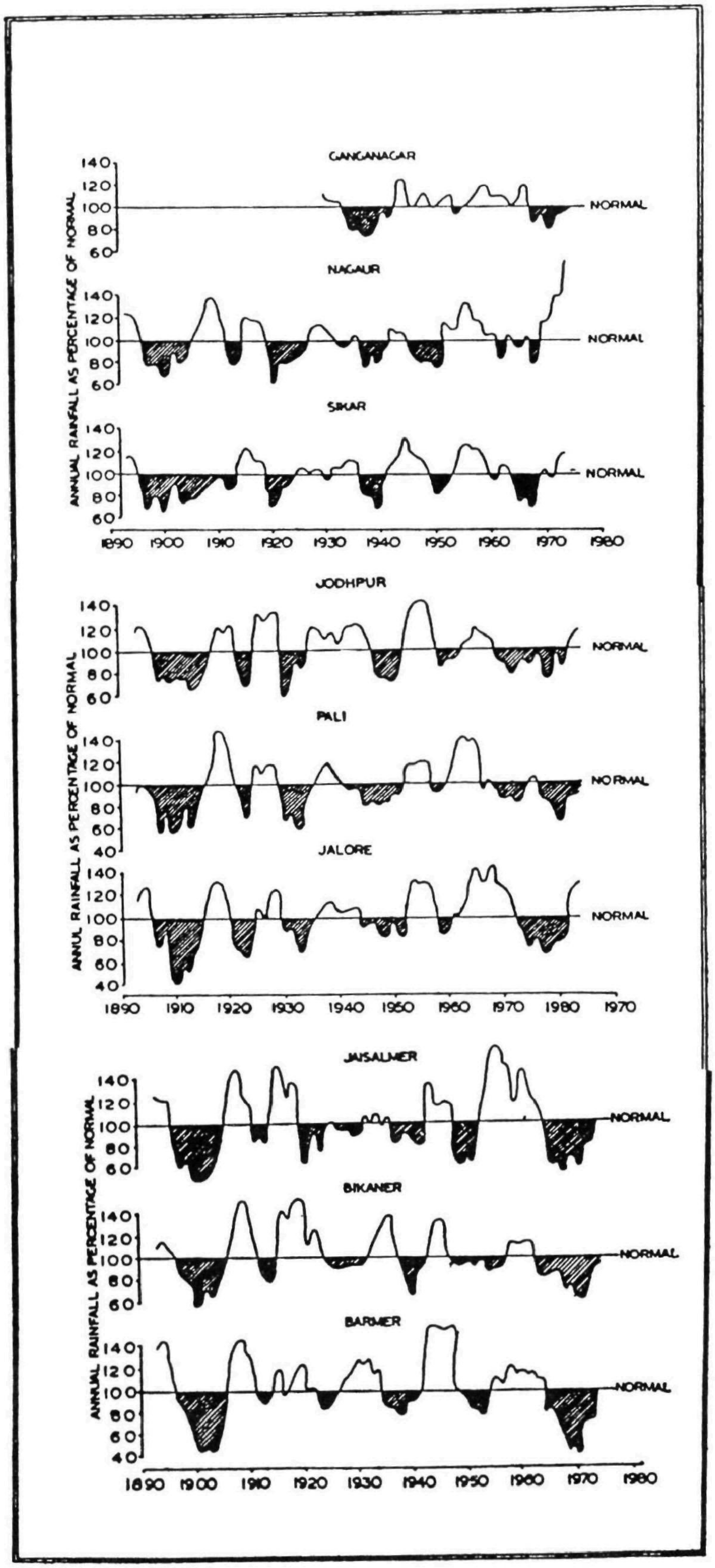


Figure 10. Five-year Moving Averages of Annual Rainfall of Arid Zone of India
Source: Krishnan 1977

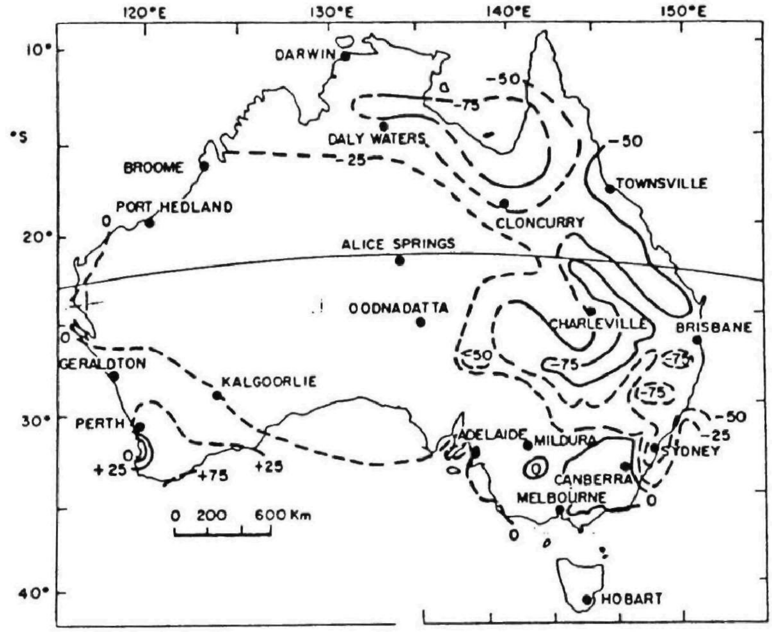


Figure 11. Changes in Mean Annual Rainfall (mm) Between the Periods 1881-1910 and 1911-1940 (Positive Values Denote Increase), Source: Gentilli 1971

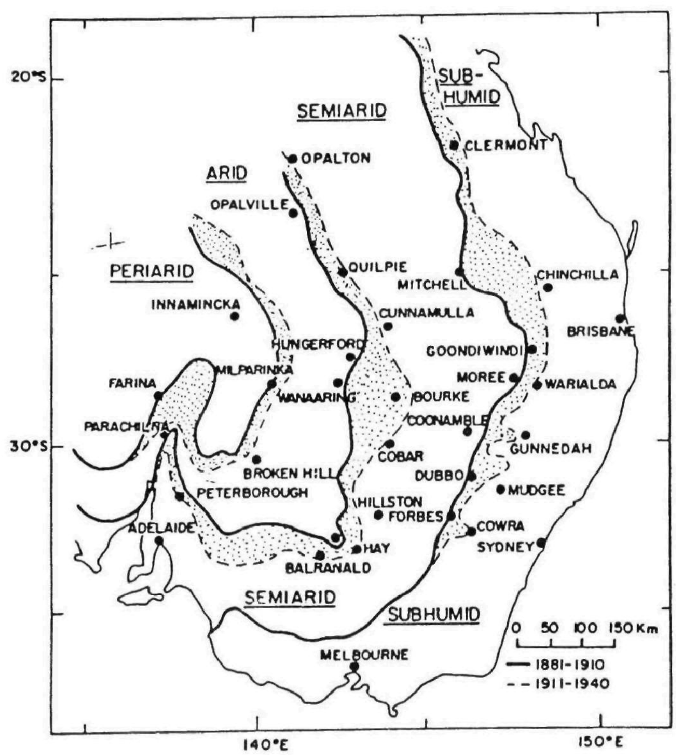


Figure 12. Shift in the Climatic Belts Over 60 Years. (Position of Boundaries in 1881-1910 Shown by Solid Line, 1911-40 by Dashed Line) Source: Gentilli 1971

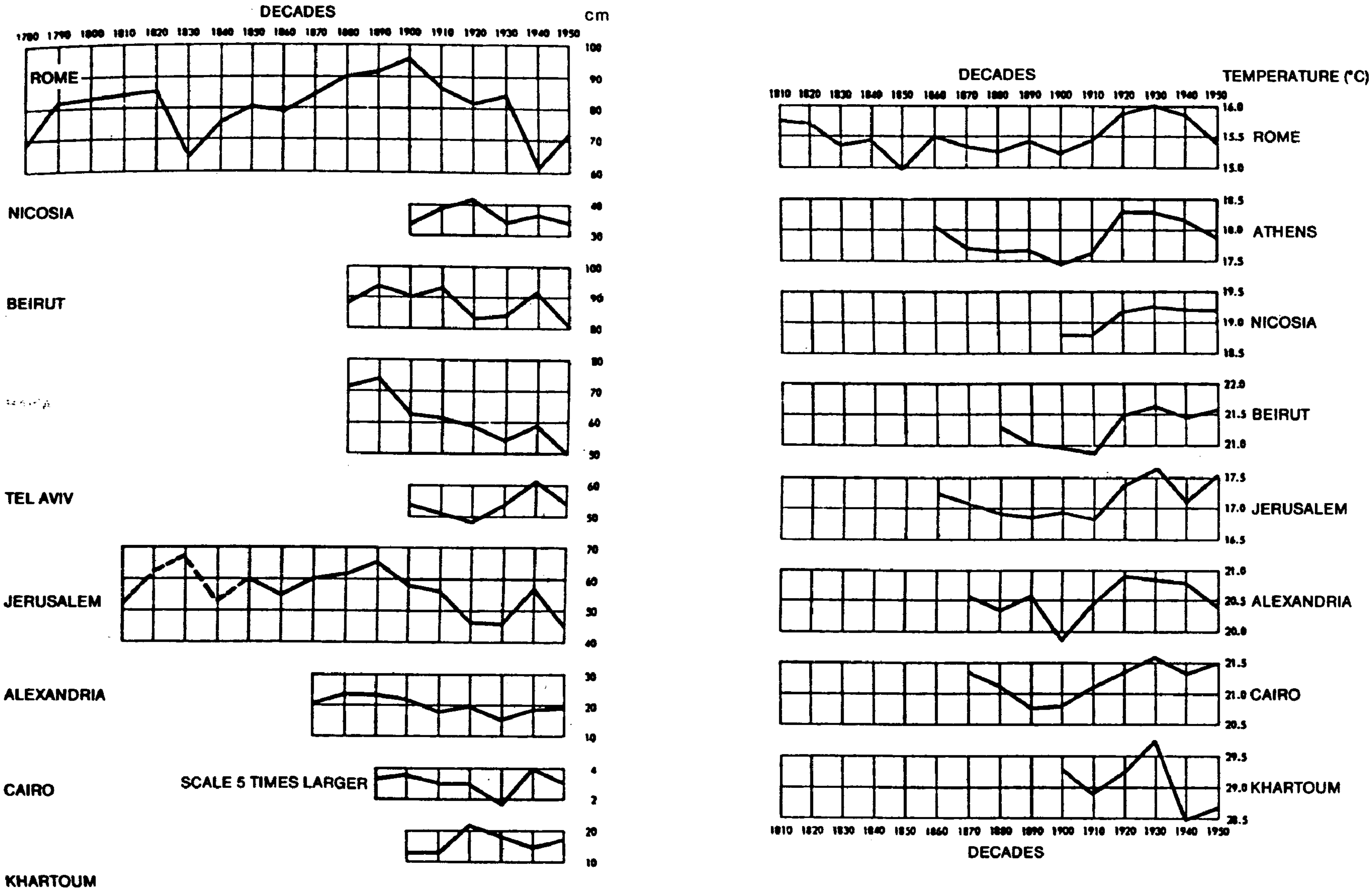


Figure 13. Ten-year Running Averages of Annual Temperature and Rainfall at Middle Eastern and Mediterranean Stations (from Rosenan 1963)

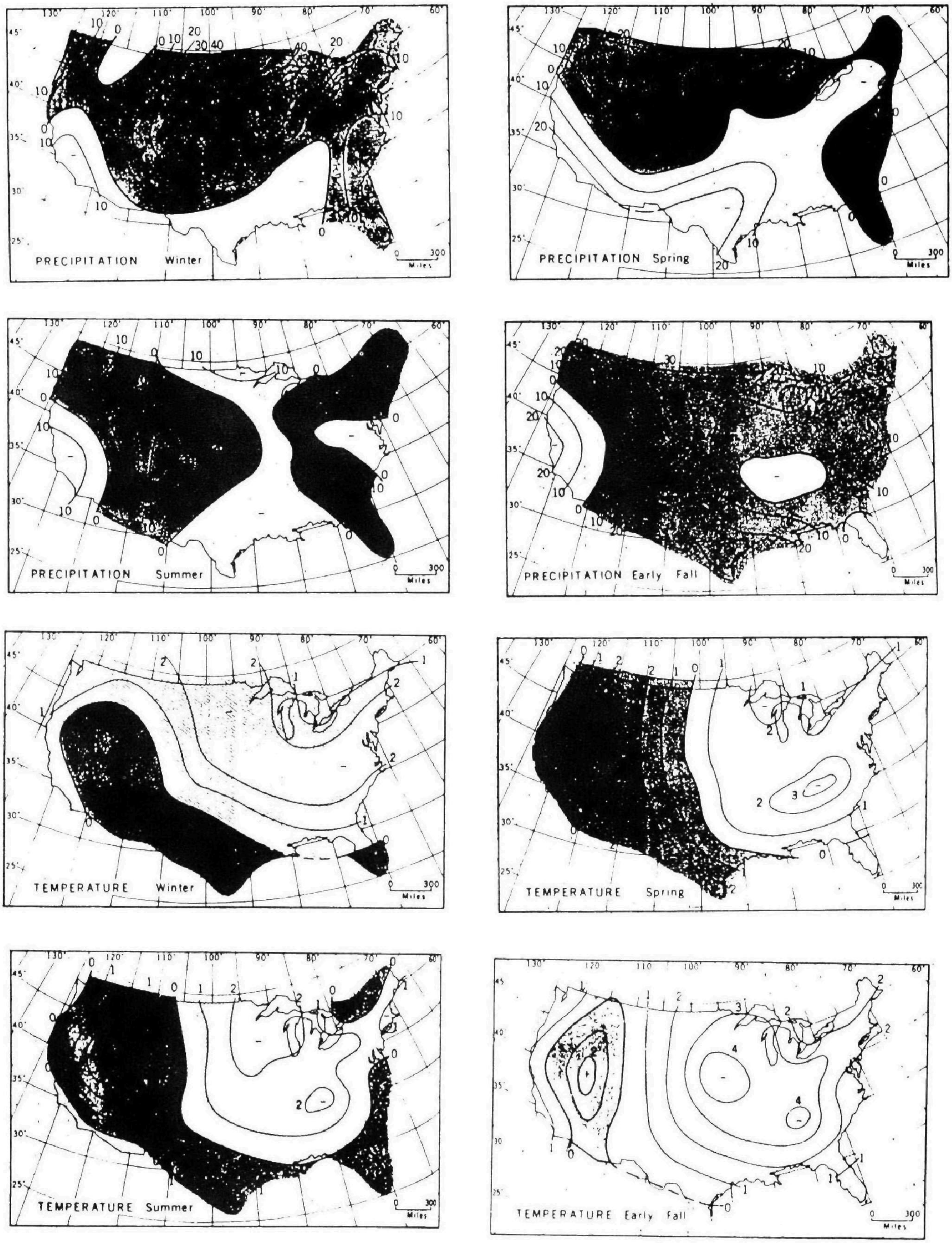


Figure 14. Precipitation (%) and temperature (°F) deviations of the period 1850 to 1870 from the 1931-60 climatic normals: A. Winter; B. Spring; C. Summer, D. Early Fall
Source: Wahl and Lawson 1970

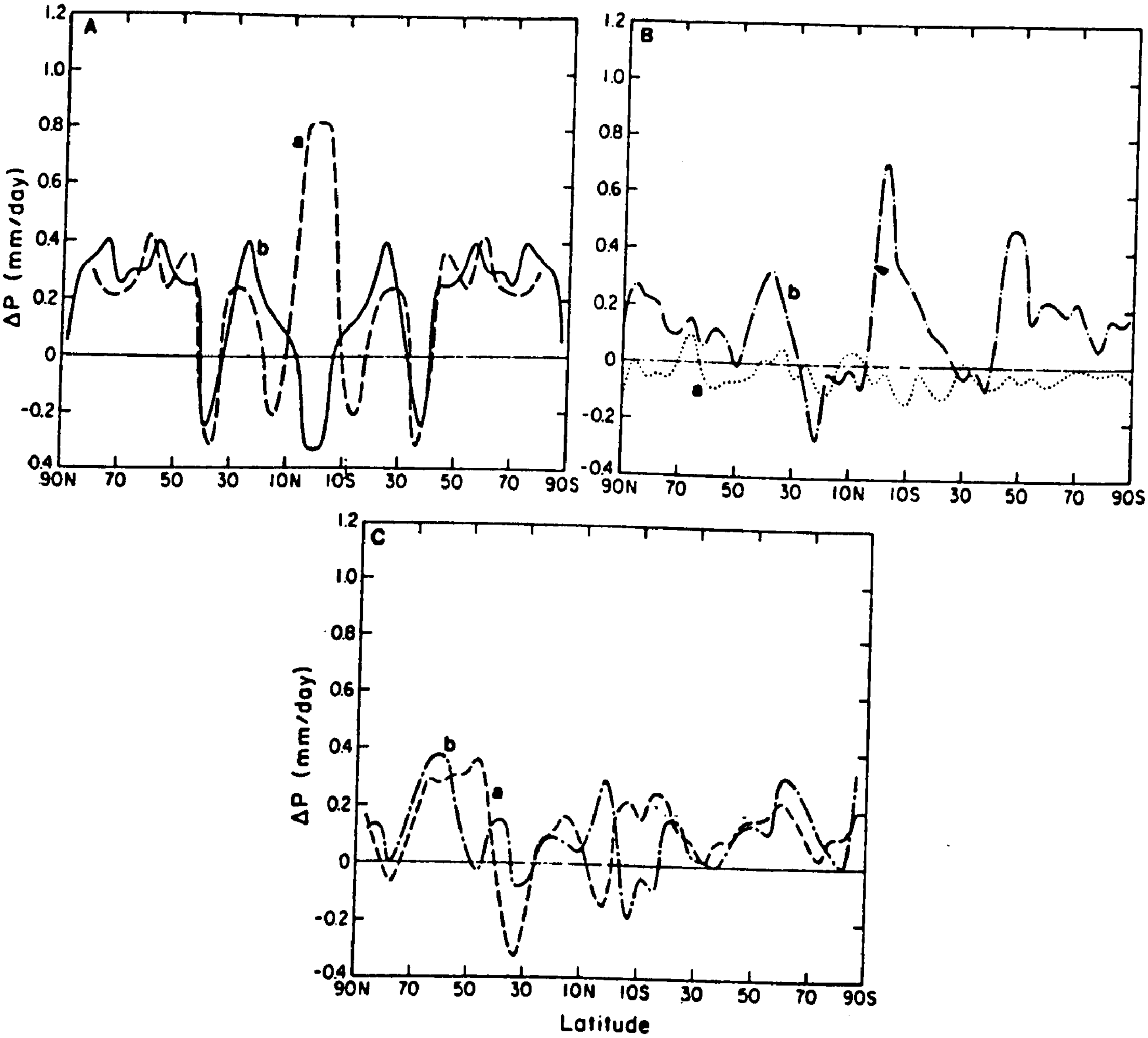
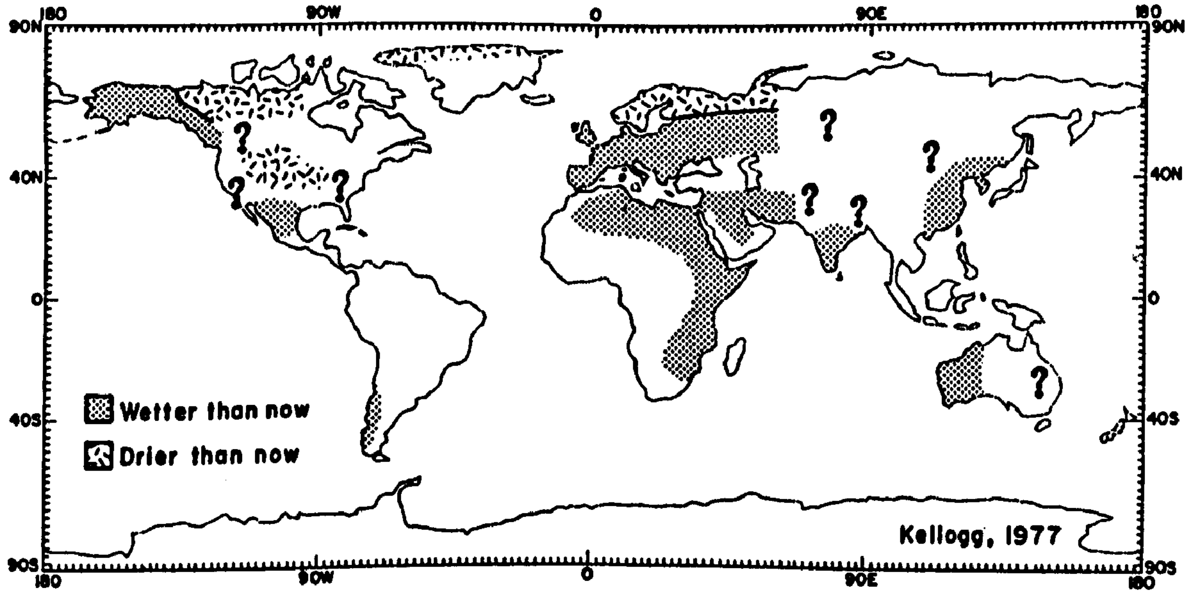


Figure 15. Change in Zonal Mean Precipitation Rate Simulated by Six GCMs for Doubled CO_2 (See Schlesinger and Mitchell 1985 for Details)



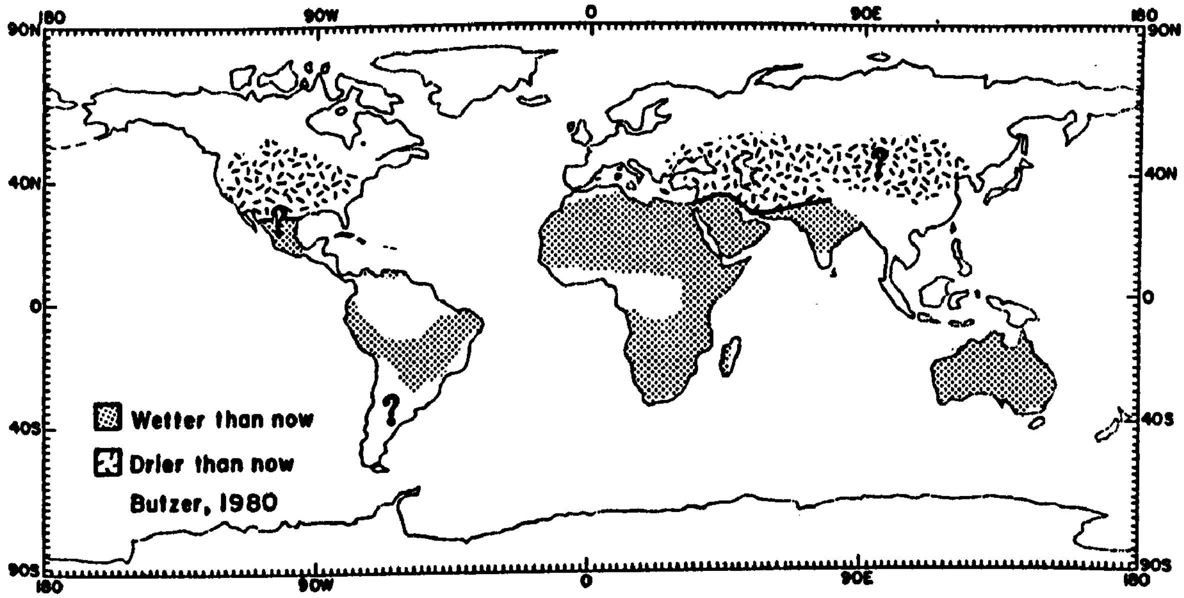


Figure 16. Two Paleoclimatic Reconstructions of the Altithermal (c. 4500 to 800 years ago)
Source: Kellogg and Schware 1981.

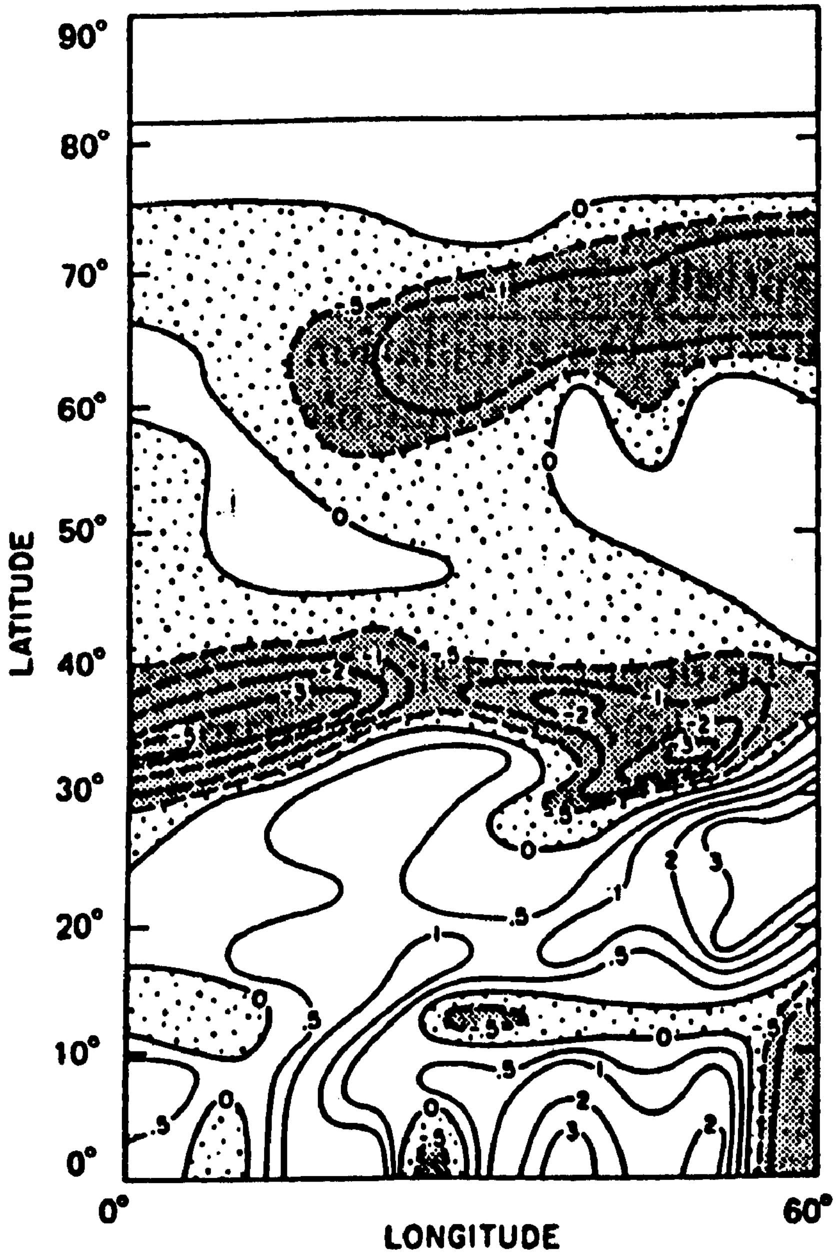


Figure 17. Simulation of Change in Soil Moisture (cm) for Doubled CO_2
Source: Manabe and Wetherald 1975

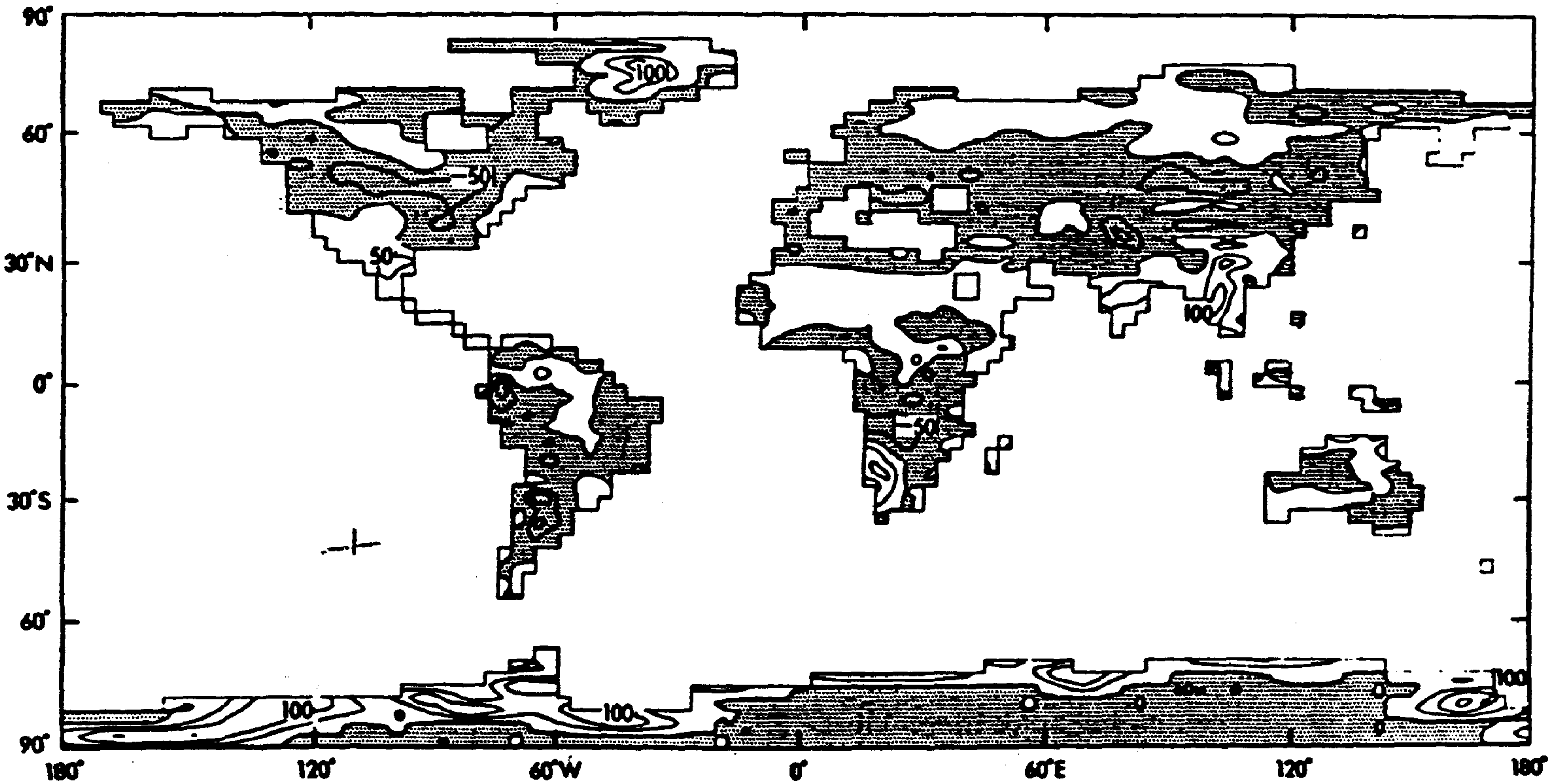


Figure 18 . Changes in Model Soil Moisture for June to August for Quadrupled CO_2
Source: Mitchell 1984

The changes of rainfall and water resources could be gradual or abrupt; they may involve changes of mean conditions, variability about the mean (i.e., the reliability of water resources from year to year) or seasonality. Even if only a change of mean conditions results, this will drastically alter the frequency of what is now perceived as "extreme" events (e.g., droughts or floods) which have severe impact on populations (Mearns, Katz, and Schneider 1984). Perhaps the best lesson of climatic history is that agricultural and economic systems must be flexible enough to adapt to changing conditions and, in the face of potential water scarcity, systems must be designed that require minimum use of resources.

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Response of Lake Levels to Climatic Change—Past, Present, and Future

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Historical and geological evidence clearly demonstrate that the water levels of lakes in North America and elsewhere have varied significantly, on time scales of 1-10^4 years, in response to climatic changes (Street and Grove 1979; Street-Perrott and Roberts 1983; Street-Perrott and Harrison 1985; Harrison and Metcalfe 1985). The largest fluctuations have been experienced by closed (terminal) lakes. A closed, sealed lake (one that has no significant surface or subsurface outflow) will attain equilibrium with the prevailing climate when:

$$z = A_L/A_B = (P_B - E_B)/(E_L - P_L),$$

where A is area, P is mean annual precipitation, E is mean annual actual evaporation or evapotranspiration, and the subscripts L and B refer to the lake and its drainage basin, respectively. In general, $P_B > P_L$ and $E_L > E_B$ (Street-Perrott and Harrison 1985).

Hence, a lake's equilibrium area, depth, and volume will increase in response to an increase in precipitation, a decrease in evaporation, or both. Because they integrate the climate over their basins, lakes are excellent indicators of regional hydrological changes.

However, it is important to know how rapidly an individual lake reaches a new equilibrium after a change in climate. For a step change in climate, it is possible to define a characteristic equilibrium response time, τ_{eg} For a closed, sealed lake, this is given by:

$$\tau_{eq} = A_L/((dA_L/dL)\ (E_L - P_L)),$$

where τ_{eq} is the time taken to achieve 1 - 1/e (63% of the equilibrium response) and L is lake depth (Mason et al. 1985). Calculated response times for some important lakes are given in Table 1. These show that many closed lakes can be expected to exhibit a fast equilibrium response to hydrological

Table 1. The Equilibrium Response Times of Selected Lakes

LAKE	TIME	A_L (10^6 m^2)	dA_L/dL (10^6 m^2/m)	E_L-P_L (m/yr)	τ_{eq} (yr)
Pyramid (USA)	1840-1920 AD	540	5.3	1.03	99
Mono (USA)	1900-1930 AD	227	1.5	0.82	187
Great Salt Lake (USA)	1850-1874 AD	6279	579.4	1.23	9
	1875-1899 AD	6196	566.0	1.29	8
	1900-1924 AD	5093	706.8	1.3	6
	1925-1949 AD	4978	709.0	1.34	5
	1950-1974 AD	4698	745.3	1.3	5
	1975-1985 AD	5908	671.2	1.09	8
George (Australia)	1958-1963 AD	153	4.7	0.19	171
	1963-1968 AD	153	7.7	0.55	36
	1968-1973 AD	135	42.3	0.89	4
	1973-1978 AD	148	42.1	0.67	5
	1978-1983 AD	146	48.7	1.26	2
Eyre (Australia)	1974-1975 AD	9790	800.0	1.47	8
Valencia (South America)	1977-1981 AD	350	8.75	1.06	38
Chad (Africa)	1967-1971 AD	22500	1712.0	1.93	7
	1972-1976 AD	20500	1563.0	1.98	7
Abiyata (Ethiopia)	1969-1974 AD	212	14.7	1.41	10
Palaeolake Abiyata	9 kyr BP	2690	22.8	1.02	116
(=Ziway Shala)	2.5 kyr BP	1590	18.0	1.18	75
Winnipeg (Canada)					2

Data from: Harding S.D., 1962, 1965; Bye J.A.T. et al., 1978; Tetzlaff G. & Bye J.A.T., 1978; Street F.A., Ph.D. thesis, 1979; Vuillaume G., 1981; Lewis, W.M., 1983; Lund L.V. et al., 1984; Australian Bureau of Meteorology, 1985; Bureau of Mineral Resources, Geology & Geophysics, A.C.T:, 1985; Kay P.A. & Diaz H.F., 1985; South Australian Engineering and Water Supply Department, 1985; Inland Waters Directorate Canada, 1985; Stauffer N.E., 1985; Mason et al., in press;

changes resulting either from increasing levels of atmospheric trace gases or from other causes operating on a similar time scale. For open lakes such as Lake Winnipeg (Table 1), τ_{eq} is given by

$$\tau_{eq} = A_L.dL/dD,$$

where D is the discharge through the outlet. In such cases, τ_{eq} tends to be very short.

This rapidity of response suggests that monitoring lake levels and/or lake areas could be a highly cost-effective way of keeping track of the regional hydrological impact of increasing levels of greenhouse gases. The number of lakes that can be measured in the field is restricted by accessibility. It would be possible, however, to measure the water levels and areas of lakes remotely from satellites using a combination of radar altimetry and an imaging instrument. These observations would supplement and be validated by ground-based measurements, but would add greatly to the coverage of remote or inhospitable areas. It would also be possible to carry out frequent and regular sampling, whose quality could be controlled for accuracy and consistency.

The radar altimeter on Seasat was capable of measuring lake levels with a precision of ± 10 cm RMS. ERS-1, due to be launched in 1989, will carry two sensors that could provide the necessary measurements: an along-track scanning radiometer (ATSR) and a radar altimeter (RA). With a 35-day repeat-track period, the RA should be able to monitor approximately 100 closed lakes of more than 100 km^2 and many more smaller lakes (Guzkowska et al. In press).

Historical data on lake-level fluctuations in the United States suggest that changes of quite large amplitude can be expected to occur in response to future climatic change. Between 1963 and 1986, for example, Great Salt Lake increased in depth by 5.9 m. It expanded in area from 2590 km^2 to over 6000 km^2 (Arnow 1984 and the New York Times, April 28, 1986), causing enormous damage to lakeside property, industry, and communications. Over the last 150 years, some lakes have fluctuated in depth by nearly 30 m (see Figure 2 in Street-Perrott and Harrison 1985). Other things being equal, since the equilibrium response of lake depth to a given change in climate is inversely proportional to A_L/A_B and dA_L/dL, the largest changes in water-surface elevation can be expected to occur in the steep-sided desert basins of the western United States, such as Winnemucca and Walker (Nevada).

Because evaporation generally increases the salinity and alkalinity of a terminal lake as its volume decreases, those that experience large variations in volume also tend to undergo very large changes in chemistry and ecology (e.g., Arnow 1984).

Climatic changes during the last 30,000 years have resulted in much larger variations in lake levels than those described above, affecting extensive regions of the earth's surface. Between 7000 and 5000 years ago, for example, lakes in many parts of North America stood at significantly lower levels than today; indeed, many presently open lakes were then closed. This period of dry conditions has been explained by reference to the orbital theory of climatic change (Kutzbach and Guetter, in press; Street-Perrott, in press). For the middle and high latitudes of the Northern Hemisphere, the orbital configuration during the early and mid-Holocene gave rise to an increase in annual net radiation of the same order as that expected to result from a doubling of CO_2, although the seasonal distribution of the forcing was different. One important way of validating the climatic predictions made using general circulation models (GCMs) is to use the same models for paleoclimatic simulations, which can then be tested against geological data. The early and mid-Holocene are particularly interesting in this respect.

A high-priority task for the future is to develop topographically and hydrologically realistic models of individual lake basins that can use the output of GCMs or other climate models as input (see Cohen, this volume). This approach will permit more rigorous comparisons between paleoclimatic simulations and geological data. It will also enable predictions of future climatic change to be translated into quantitative measures of surface-water availability, provided that a rigorous method can be devised to cope with the mismatch in scale between the two types of model.

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Regional Water Resources and Global Climatic Change

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ABSTRACT

Concern over changes in global climate caused by growing atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and global climate systems has improved. Yet, despite a growing understanding of climatic processes, many of the effects of human-induced climatic changes are still poorly understood. The most profound effect of such climatic changes may be major alterations in regional hydrologic cycles and changes in regional water availability. Unfortunately, these are among the least understood impacts.

This paper discusses the applicability of modified water-balance methods for evaluating regional hydrologic impacts of global climatic changes. Such methods offer considerable advantages over other hydrologic methods for identifying the sensitivity of regional watersheds to future changes in temperature, precipitation, and other climatic variables. Furthermore, such methods can be combined with information from both general circulation models of the climate and with hypothetical scenarios to generate information on the water-resource implications of plausible future climatic changes.

Water-balance modeling techniques modified for assessing climatic impacts have been developed and tested for a major watershed in northern California using climate-change scenarios from both state-of-the-art general circulation models and from a series of hypothetical scenarios. Results of this research suggest strongly that plausible changes in temperature and precipitation caused by a doubling of atmospheric carbon-dioxide concentration would have major impacts on both the timing and magnitude of runoff and soil moisture in important agricultural areas. Of particular importance are predicted patterns of summer soil moisture drying that are consistent across the entire range of tested scenarios. In addition, consistent changes in the timing of runoff--specifically, significant increases in winter runoff and decreases in summer

runoff--raise the possibility of major difficulties for future water-resource planning.

INTRODUCTION

Concern over the possible impacts of changes in global climate caused by increasing atmospheric concentrations of carbon dioxide and other trace gases has grown in recent years as our understanding of atmospheric dynamics and climatic systems has improved. Despite a better understanding of climatic processes, however, the possibility of major alterations in regional hydrologic cycles and subsequent changes in regional water availability are among the least understood impacts.

One of the most useful tools for evaluating global-averaged climatic changes due to increased CO_2 concentrations is the general circulation model (GCM) of the climate. Yet state-of-the-art GCMs, though much advanced over early versions, are still limited in their ability to incorporate details on small-scale hydrologic processes or regional climate. As a result, alternative techniques for evaluating regional hydrologic consequences must be developed, tested, and applied.

One attractive method for looking at impacts of climatic changes on water supplies involves combining regional hydrologic modeling (water balance) techniques with information on plausible climatic changes from both hypothetical scenarios and from state-of-the-art GCMs. This method can produce information on the sensitivity of water availability in regional watersheds to changes in temperature and precipitation. Appropriate water-balance modeling techniques have been developed and tested for a major watershed in northern California (Gleick 1986b).

Results of this research suggest strongly that plausible changes in temperature and precipitation caused by increases in atmospheric trace gas concentrations would have major adverse impacts on both the timing and magnitude of runoff and soil moisture in important agricultural areas. Some of the most important of the changes in runoff and soil moisture are robust across a wide range of climate-change scenarios. These hydrologic results will have significant implications for future water-resource planning and for international environmental and political behavior.

THE PROBLEM

As fossil-fuel use and industrial development expanded over the last century, the atmospheric concentration of carbon dioxide and other radiatively active trace gases has also risen. Only within the last two decades, however, have serious scientific efforts investigated the geophysical ramifications.

Climate affects most of the world's environmental conditions--the supply of food and water, the need for shelter, the accessibility of mineral resources, the distribution of flora and fauna, and so on. Even short-term variations in climatic conditions can cause enormous human suffering. The possibility that global climate may change permanently as a result of human activities must be cause for substantial international concern, and perhaps alarm.

Although we can presently conceive of ways in which global climate may be affected by our actions, we are unable to see clearly either the direction of changes in climate or the societal impacts of such changes. Because we cannot conduct controlled experiments on the entire planet, we must attempt to model climate and climatic changes--an imprecise alternative because of the complexity of the global climate system. Because of the many intricate and intertwined phenomena that make up the climate, much of the effort of trying to understand the climate system has focused on the development of large-scale computer models. The most complex of these are detailed, time-dependent, three-dimensional numerical programs that include atmospheric motions, heat exchanges, and important land-ocean-ice interactions. These models are typically referred to as "general circulation models" or "global climate models" (GCMs).

GCMs have permitted us to begin to evaluate some of the implications for climatic patterns of increasing concentrations of atmospheric gases, and a consensus is beginning to form about both the direction and magnitude of certain major impacts, such as increases in global average temperatures and changes in the intensity of distribution of the global hydrologic cycle.

General circulation models are large and expensive to operate. While they are invaluable for identifying climatic sensitivities and changes in global climatic characteristics, they have two particular limitations to their usefulness to researchers interested in more detailed climate impact assessment: GCMs cannot provide much detail on regional or local climate impacts, nor can they provide much detail on surface hydrology. For these reasons, new methods must be developed that can incorporate information on both hypothetical and predicted climatic changes in order to determine how future global changes may affect regional water resources and water availability.

METHODS FOR REGIONAL HYDROLOGIC STUDIES OF CLIMATIC CHANGE

Recently there have been initial attempts to evaluate the regional hydrologic implications of climatic changes (Schwarz 1977; Stockton and Boggess 1979; Nemec and Schaake 1982; Revelle and Waggoner 1983; Flaschka 1984; Rind and Lebedeff 1984). These early works provided the first tentative evidence that relatively small changes in regional precipitation and evaporation patterns might result in significant, perhaps critical, changes in regional water availability.

Before realistic estimates of changes in regional water availability can be calculated, however, improvements must be made in several areas. Among the most important characteristics of regional hydrologic assessments should be a focus on short time-scales (i.e., months and seasons, rather than annual averages); the ability to incorporate both hypothetical climatic changes and the increasingly detailed assessments of regional changes produced by GCMs; the use of methods that produce information on hydrologically important variables, such as changes in soil moisture and runoff; and the incorporation of the complexities of snowfall and snowmelt, topography, soil characteristics, and natural artificial storage.

One of the most promising methods for doing regional hydrologic assessments of global climatic changes is the use of water-balance models modified for conditions of changing climate (Gleick 1986a). Water-balance methods are useful in diverse watersheds. They can evaluate changes in vegetative cover, snowfall and snowmelt rates; characteristics of groundwater recharge and withdrawal; and monthly and seasonal responses. They can be developed and run on existing generations of state-of-the-art general circulation models.

A Water-Balance Model for Climatic Impact Assessment

We developed a water-balance model to evaluate the capabilities of such models for climate impact assessment. This model was then tested and used to evaluate hydrologic impacts of changes in climate in the most important hydrologic basin in California and one of the most important in the United States--the Sacramento Basin (see Figure 1).

The Sacramento Basin provides over 30% of the total runoff for the state of California, including almost all of the water used for agriculture in the Central Valley--one of the most productive agricultural regions of the world. Moreover, the water resources of this basin are already heavily subscribed--hence any climatic change that decreases total water availability or significantly changes the timing of soil moisture and runoff would affect the social and physical environment of the region. Details of the development of the model, the modifications of the model for use under scenarios of changing climate, and the statistical verification of the model are presented in Gleick (1986a, 1986b).

To determine the effect of changing climate on the water resources of this region, we developed a series of temperature and precipitation scenarios and used them to drive the water-balance model. For the purposes of this study, both purely hypothetical climate-change scenarios and scenarios developed for general circulation model output were chosen for analysis. The hypothetical scenarios of temperature and precipitation changes were chosen after reviewing state-of-the-art estimates of future changes in climatic conditions. The GCM precipitation and temperature scenarios were developed after discussions with leading climate modelers in the United States and after a review of model capabilities and design. These scenarios can be summarized as follows:

- Ten hypothetical scenarios involving combinations of plus 2° and plus 4°C and +20%, +10%, 0%, -10%, and -20% changes in precipitation

- Eight scenarios of temperature and precipitation changes predicted for this general region by three state-of-the-art general circulation models: the Geophysical Fluid Dynamics Laboratory (GFDL) model (Manabe and Stouffer 1980; Manabe, Wetherald, and Stouffer 1981), the Goddard Institute for Space Sciences (GISS) model (Hansen et al. 1983, 1984), and the National Center for Atmospheric Sciences Community Climate Model (NCAR CCM) (Washington and Meehl 1983, 1984).

None of the hypothetical or GCM-derived scenarios includes decreases in average monthly temperatures, because of the consensus in the climate community that increasing concentrations of carbon dioxide and other trace

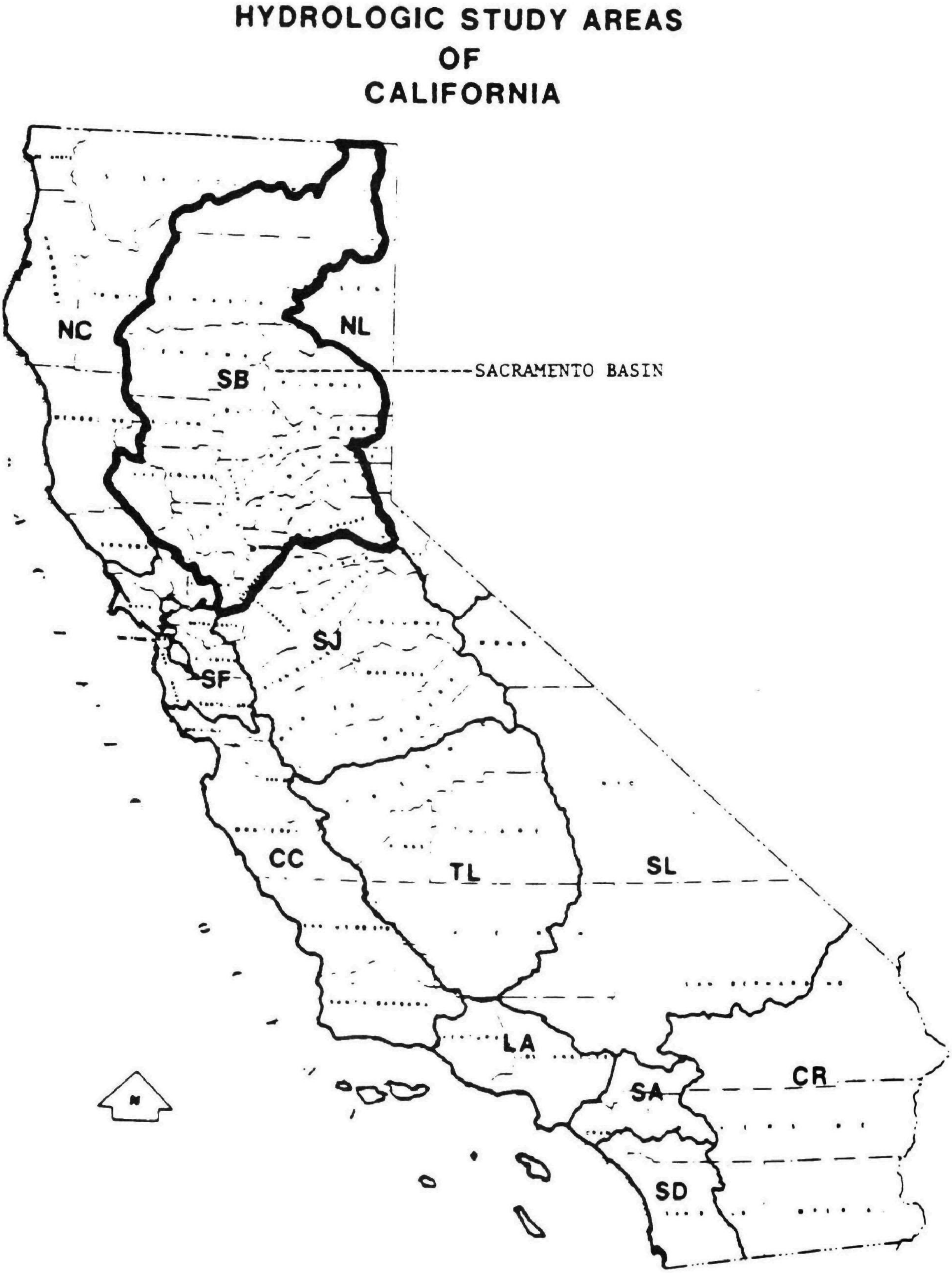

Figure 1. The Scramento Basin, California

gases will lead to increases in surface air temperature on both a global and a regional scale. This consensus has been expressed as a 95% probability that an "equivalent doubling" of atmospheric carbon dioxide--the injection into the atmosphere of CO_2 and other trace gases such that the climatic effect of the combined gases is equivalent to the climatic effect of a doubled concentration of CO_2 alone--will result in an average global warming of between 1.5° and 5.5°C, with a most likely temperature increase of 3.0°C ±1.5°C (Dickinson 1984). Current GCMs suggest that broad regional temperature increases will exceed these values, particularly in polar latitudes. Temperature increases of 2° and 4°C, however, are reasonable expectations for the region considered in this paper.

Global average precipitation is predicted to increase 5-10% under an equivalent doubling of atmospheric carbon dioxide, due primarily to the increase in global average temperature (and, hence, evaportranspiration) (Manabe and Wetherald 1975, 1980). Regional variations are also expected to be significant, with evidence for both increases and decreases occurring in different regions. Revelle and Waggoner (1983) evaluated changes of ±10% in a series of U.S. watersheds, and both Nemec and Schaake (1982) and Flaschka (1984) chose scenarios of ±10-25%. For the purpose of this study, five precipitation scenarios were evaluated: no change in monthly average precipitation, increases in monthly average precipitation of 10% and 20%, and decreases in monthly average precipitation of 10% and 20%. Because actual precipitation changes may exceed these values, the scenarios studied here can be considered conservative in that they explore the sensitivity of water-resources characteristics to changes in precipitation that are well within the realm of possibility.

Data from the three GCMs were obtained after a series of discussions with leading climate modelers. It must be noted that individual grid-point data, made available by each of these modeling groups, do <u>not</u> represent realistic predictions of the expected climate at these grid points. The current generation of GCMs does not permit detailed regional estimates of climatic changes because of limitations on computer time and speed, model resolution, major physical parameterizations, and existing data sets. GCM modelers understand these limitations. Nevertheless, the researchers at the three climate centers agreed to provide grid-point data so that we might evaluate (and confirm or dispute) hydrologic effects seen in general circulation model results and help to gain a better understanding of both the differences and similarities among the models, and the sensitivity of hydrologic systems to climatic changes. Thus, while the scenarios developed by the GCMs should not be treated as a more likely description of the future than any other scenario, they do offer insights into both the capabilities of GCMs and their estimates of hydrologic responses.

The <u>differences</u> among the GCM scenarios also provide some advantages. First of all, they highlight some of the limitations of GCM grid-point estimates and GCM model resolution. Second, by evaluating different predicted temperature and precipitation scenarios, we can evaluate a wide range of climatic changes. Third, by incorporating these scenarios, it may be possible to identify areas in which consistent changes in soil moisture or runoff may be obtained <u>despite</u> widely varying precipitation and temperature inputs. This result would indicate areas of important hydrologic sensitivity and would certainly be worthy of additional attention.

The eighteen scenarios (summarized in Table 1) were used to drive the water-balance model of the Sacramento Basin and to estimate the effects on available soil moisture and runoff. For every scenario, a new 50-year record of monthly average temperature and precipitation was created by applying the hypothetical changes to the 50-year historical record of monthly average temperature and precipitation in the Sacramento Basin. These data inputs were then used to drive the water-balance model, producing a 50-year record of monthly runoff and available soil moisture. These data were then averaged, to produce long-term average monthly and average seasonal runoff and soil-moisture results.

RUNOFF AND SOIL MOISTURE RESULTS

Major hydrologic changes resulted from the eighteen scenarios, including some changes that are consistent in their direction in every scenario despite significant differences in the original precipitation and temperature inputs. These changes include alterations in the magnitude of runoff and soil moisture, as well as important changes in the timing of runoff and soil moisture.

HYPOTHETICAL CLIMATE-CHANGE SCENARIOS

Significant changes in runoff patterns were observed for all of the hypothetical scenarios. On an annual basis, the direction of the change in runoff from the different temperature and precipitation scenarios was unsurprising: temperature increases alone led to decreases in annual runoff; temperature increases combined with increases in precipitation of 10% and 20% resulted in increases in annual runoff; temperature increases combined with decreases in precipitation of 10% and 20% resulted in decreases in annual runoff.

Because shorter term hydrologic changes are of greater interest to water-resource planners than annual average changes, both seasonal and monthly impacts were studied. Two "seasons" were evaluated--winter (assumed to be the sum of December, January, and February runoff) and summer (assumed to be the sum of June, July, and August runoff). These assumptions are consistent with most GCM analyses of seasonal climatic variables. They also correspond well to actual seasonal conditions in the Sacramento Basin, which receives much of its precipitation during winter months.

Changes in Average Summer and Winter Runoff

Summer runoff in all the hypothetical scenarios is reduced significantly and consistently when compared to summer runoff in the base case. Although the reduction in runoff is most pronounced in those runs where monthly average temperature is increased and monthly average precipitation is reduced, reductions in summer runoff are also evident when monthly average precipitation is increased significantly. The most dramatic example of this is a reduction in summer runoff of nearly 50% when monthly average temperature increases 4°C and monthly average precipitation increases 20%. Even an increase in the monthly average temperature of only 2°C combined with an increase in monthly precipitation of 20% does not increase total summer

Table 1. Climate-Change Scenarios

Hypothetical Climate-Change Scenarios[1]

Change in Monthly Temperature (°C)	Change in Monthly Precipitation
T + 2°	No Change
T + 2°	- 10%
T + 2°	- 20%
T + 2°	+ 10%
T + 2°	+ 20%
T + 4°	No Change
T + 4°	- 10%
T + 4°	- 20%
T + 4°	+ 10%
T + 4°	+ 20%

General Circulation Model Climate-Change Scenarios[1]

Geophysical Fluid Dynamics Laboratory (Princeton, New Jersey)

- Temperature Changes Only
- Temperature and Relative Precipitation Changes
- Temperature and Absolute Precipitation Changes

Goddard Institute for Space Sciences (New York, New York)

- Temperature Changes Only
- Temperature and Relative Precipitation Changes
- Temperature and Absolute Precipitation Changes

National Center for Atmospheric Research (Boulder, Colorado)

- Temperature Changes Only
- Temperature and Absolute Precipitation Changes

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1 The temperature and precipitation change scenarios in this table were used to drive a water-balance model of a major hydrologic basin. See text for details.

runoff. Table 2 summarizes the percent reductions in summer runoff from the ten hypothetical scenarios. Figure 2 plots the percent changes in average summer runoff for the ten hypothetical scenarios.

For both the T + 2° and T + 4°C cases, the temperature increases account for a large fraction of the total reduction in summer runoff. The next section details, the reduction in summer runoff results from a major shift in the timing of runoff due to change in rain/snow ratios in winter and the speed of snowmelt in the spring. Winter runoff shows a similar pattern. Increases in temperature alone cause increases in average winter runoff due to a decrease in the proportion of snow to rain and hence a decrease in the storage of water (the snowpack) during the winter. For the T + 2°C run with no change in precipitation, winter runoff increases 8%; for the T + 4°C run with no change in precipitation, winter runoff increases dramatically by 34%.

When precipitation changes are imposed on the temperature increases, winter runoff results become mixed--for T + 2°C runs, increases in precipitation cause increases in winter runoff, and decreases in precipitation cause decreases in winter runoff. For the T + 4°C runs, however, the winter runoff changes are, for the most part, positive. For all the runs except one, changes in precipitation lead to increases in winter runoff. The one exception is the extreme--a decrease in monthly precipitation of 20%. Even in this case, however, the decrease in average winter runoff is small--only 4%. The percent changes in average winter runoff are plotted in Figure 3. Table 3 summarizes these results.

Some of the changes in average winter runoff are extremely large, particularly in the runs with increases in precipitation. Increases in winter precipitation of only 20% lead to increases in average winter runoff of 40% to 80% for the T + 2°C and T + 4°C runs, respectively. Such dramatic increases in runoff raise concerns about the possibility of increased flooding, especially in basins with flood-control systems designed for different hydrologic conditions, or in basins without major reservoirs.

Changes in Average Monthly Runoff

The full consequences for runoff of climatic changes can be seen when average monthly runoff is studied. Here we see the importance of looking at temporal variations in runoff on a scale shorter than the annual cycle. When looking only at the average annual figures, the decrease in runoff from a 4°C increase in average temperature is only 7% (see Table 4). When individual average monthly changes are evaluated, however, we see that the same increase in temperature of 4°C causes an increase in average January runoff of 39% and a decrease in average June and July runoff of nearly 70%. Dramatic changes in the timing of monthly runoff are thus hidden when only the effects on average annual values are considered.

For all ten hypothetical scenarios we estimated significant shifts in the timing of monthly runoff. While the increase in average temperature is a major driving force for these shifts, the changes in precipitation contribute to and amplify the effects. The cause of the shift in the timing of runoff is a decrease in total winter snowfall and an earlier and faster spring melting of the winter snowpack. Even in those cases where overall precipitation decreases, the distribution of runoff over the year changes so that spring and summer runoff decrease while runoff during the winter months increases.

Table 2. Effect of Hypothetical Temperature and Precipitation Scenarios on Average Summer (JJA) Runoff

(Percent Change over Base Run)

Precipitation Change / Temperature Change	-20%	-10%	0	+10%	+20%
T + 2°C	-42	-32	-22	-12	-1
T + 4°C	-73	-68	-62	-55	-49

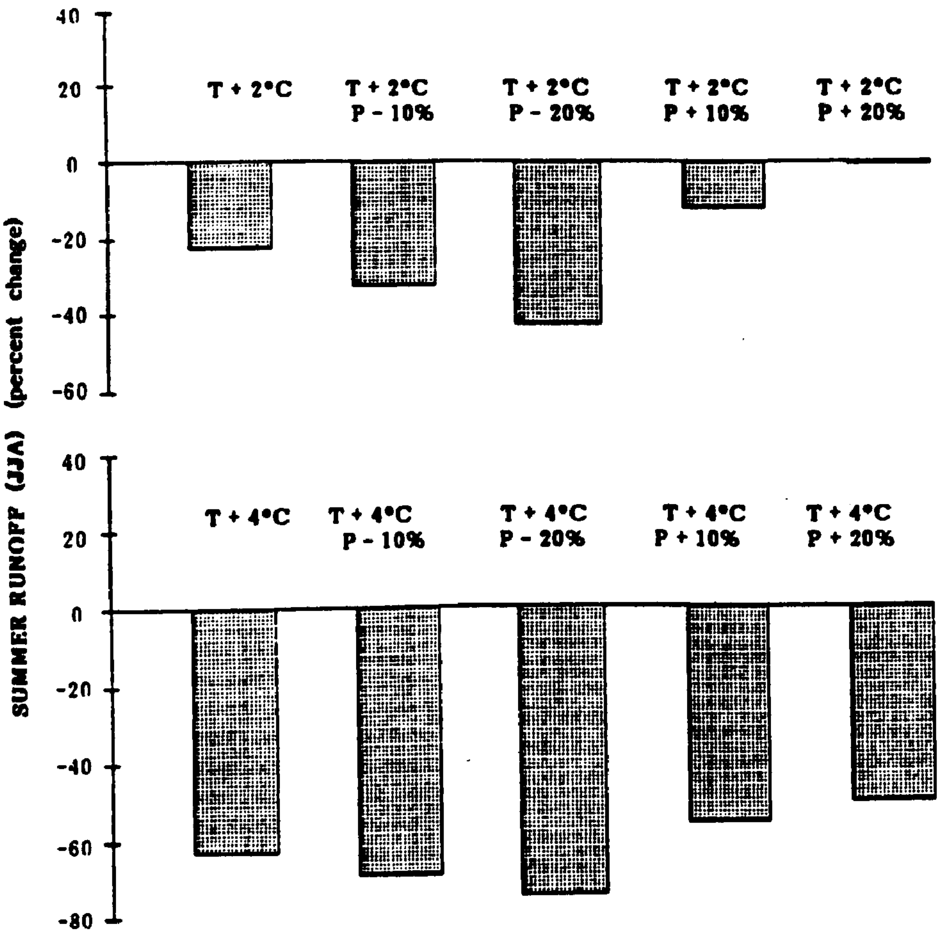

Figure 2. Percent Change in Average Summer (June, July, August) Runoff for the Ten Hypothetical Scenarios

Table 3. Effect of Hypothetical Temperature and Precipitation Scenarios on Average Winter (DJF) Runoff

(Percent Change over Base Run)

Precipitation Change / Temperature Change	-20%	-10%	0	+10%	+20%
T + 2°C	-24	-9	+8	+25	+44
T + 4°C	-4	+14	+34	+54	+75

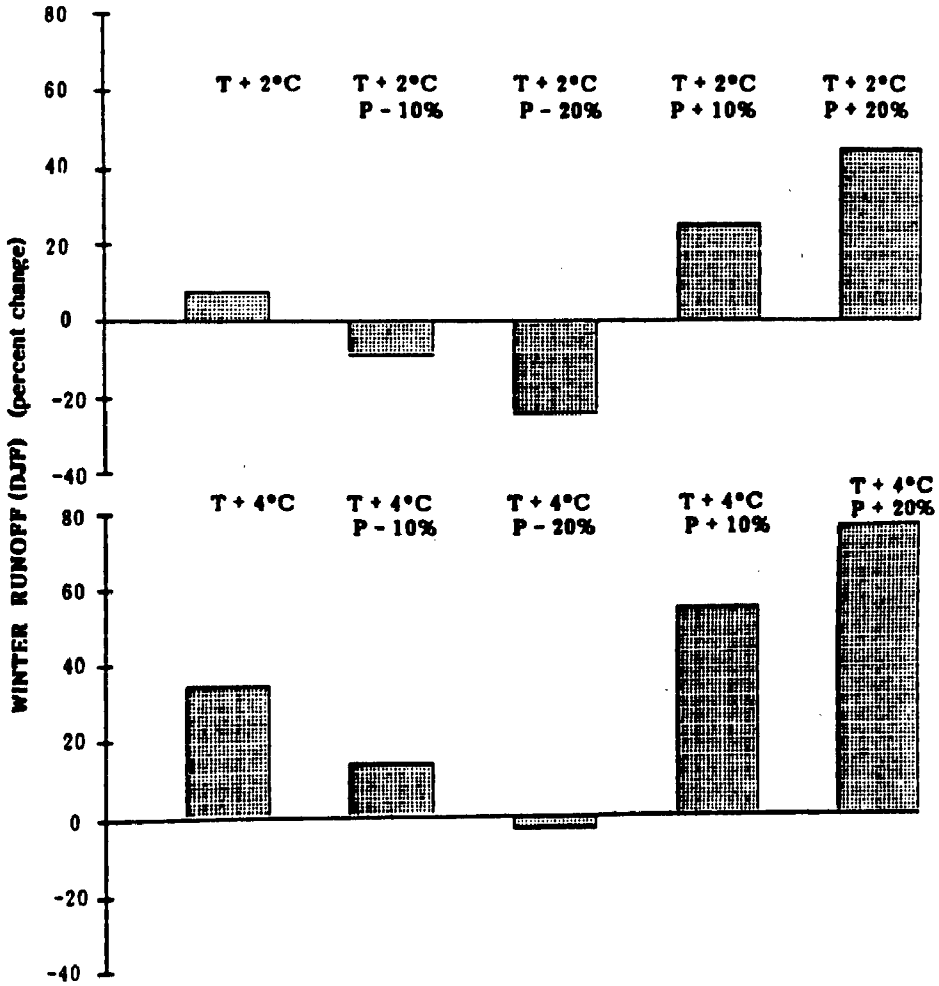

Figure 3. Percent Change in Average Winter (December, January, and February Runoff for the Ten Hypothetical Scenarios

Table 4. Effect of Hypothetical Temperature and Precipitation Scenarios on Average-Monthly and Average-Annual Runoff: A Summary

(1000 Acre-feet and Percent Change over Base Run)[1]

Run[2]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Base	2118	2245	2660	2481	1951	1285	773	492	348	401	882	1611	17245
T+2C	2234	2370	2822	2323	1649	1027	591	374	278	345	852	1828	16693
	.05	.06	.06	-.06	-.15	-.20	-.24	-.24	-.20	-.14	-.03	.13	-.03
T2P1	1879	1971	2368	1973	1418	891	514	328	246	299	731	1581	14200
	-.11	-.12	-.11	-.20	-.27	-.31	-.33	-.33	-.29	-.26	-.17	-.02	-.18
T2P2	1554	1605	1957	1655	1203	763	443	284	216	257	613	1353	11903
	-.27	-.29	-.26	-.33	-.38	-.41	-.43	-.42	-.38	-.36	-.31	-.16	-.31
T2P3	2615	2780	3277	2685	1884	1165	667	420	311	394	978	2097	19271
	.23	.24	.23	.08	-.03	-.09	-.14	-.15	-.11	-.02	.11	.30	.12
T2P4	3001	3227	3738	3046	2122	1303	744	466	343	441	1112	2387	21930
	.42	.44	.41	.23	.09	.01	-.04	-.05	-.01	.10	.26	.48	.27
T+4C	2947	2920	2806	1940	1078	556	262	163	150	264	784	2113	15984
	.39	.30	.05	-.22	-.45	-.57	-.66	-.67	-.57	-.34	-.11	.31	-.07
T4P1	2520	2474	2359	1637	908	469	220	139	131	227	670	1831	13586
	.19	.10	-.11	-.34	-.53	-.63	-.72	-.72	-.62	-.43	-.24	.14	-.21
T4P2	2130	2047	1954	1351	748	387	181	116	113	195	557	1574	11354
	.01	-.09	-.27	-.46	-.62	-.70	-.77	-.76	-.68	-.51	-.37	-.02	-.34
T4P3	3398	3395	3270	2264	1259	648	306	189	170	305	902	2408	18513
	.60	.51	.23	-.09	-.35	-.50	-.60	-.62	-.51	-.24	.02	.49	.07
T4P4	3866	3888	3735	2598	1444	742	352	215	189	345	1028	2724	21126
	.83	.73	.40	.05	-.26	-.42	-.54	-.56	-.46	-.14	.17	.69	.23

Notes to Table 4.

[Please note that the runoff values are given in acre-feet, the standard unit for runoff in all available U.S. databases. The conversion to cubic meters (m^3) is 1233 m^3 per acre-foot.]

1. The decimal values on the lines following each run are the percentage change in runoff between the model run and the base run, or $(RO_{model} - RO_{base})/(RO_{base})$. Thus, average-January runoff for the T + 2 degrees C ("T+2C") run increased by 0.05, or 5 percent, over the base run ("Base"). Similarly, average-annual runoff for the same run decreased by 0.03, or 3 percent. Average-January runoff for the T4P4 run (the last run in the table above) increased by 0.83, or 83 percent, over the base run, while average-annual runoff for this run increased by 23 percent.

2. Runs are coded as follows:

Base: Base run using historical temperature and precipitation.
T + 2C: Temperature increase of 2 degrees Celsius.
T2P1: T + 2 C; Precipitation decrease of 10 percent.
T2P2: T + 2 C; Precipitation decrease of 20 percent.
T2P3: T + 2 C; Precipitation increase of 10 percent.
T2P4: T + 2 C; Precipitation increase of 20 percent.
T + 4C: Temperature increase of 4 degrees Celsius.
T4P1: T + 4 C; Precipitation decrease of 10 percent.
T4P2: T + 4 C; Precipitation decrease of 20 percent.
T4P3: T + 4 C; Precipitation increase of 10 percent.
T4P4: T + 4 C; Precipitation increase of 20 percent.

Figures 4 and 5 show the average monthly runoff, the average annual runoff, and the percent change in these values compared to the base run for each of the ten hypothetical scenarios.

The changes in the timing of runoff occur primarily because of the increase in average temperatures, which has two effects: a significant decrease in the proportion of winter precipitation that falls as snow and an earlier and shorter spring snowmelt. The first effect causes greater winter rainfall and hence winter runoff, since less overall precipitation enters the snowpack to be held over until spring snowmelt. The second effect intensifies spring runoff, leading to additional adverse consequences for both summer runoff levels and soil-moisture levels throughout the spring and summer.

Changes in both the timing and magnitude of runoff are extremely important for water availability. Yet changes in runoff alone do not tell us all there is to know about the vulnerability of a region to changes in water-resource characteristics--changes in other variables must also be evaluated. Perhaps the most important of these is the change in the soil moisture available to agriculture and other plant communities. Soil moisture is one of the most valuable measures of water availability for agricultural development and productivity, and it is a major determinant of vegetative types and extent. The next section describes in detail the changes in soil moisture in this basin that are expected to occur from the changes in temperature and precipitation described above.

Changes in Average Summer and Winter Available Soil Moisture

Average summer soil-moisture values in the agricultural portion of the Sacramento Basin, defined as the sum of June, July, and August soil moisture, show significant and consistent decreases from the base case for all ten hypothetical scenarios. These decreases range from 8% to 44%. The minimum decrease of 8% results from a temperature increase of 2°C combined with the maximum increase in average precipitation of 20%. The maximum decrease in average summer soil moisture of 44% results from a 4°C increase in temperature combined with a 20% decrease in average precipitation. These results are summarized in Table 5. Percent changes in average summer soil moisture are plotted in Figure 6 for all ten hypothetical temperature and precipitation scenarios.

Winter soil-moisture values also show widespread decreases in the lower basin--seven of the ten scenarios result in reduced average winter soil moisture. The magnitude of the reductions is not nearly as large as the reductions in summer soil moisture, but the winter reductions offer some additional insights into the sensitivity of watersheds to changes in climate. Temperature increases alone reduced winter soil moisture by 4% and 9% for 2° and 4°C increases, respectively. These reductions are the result of increased evapotranspiration rates. Of greater interest is the fact that soil-moisture increases were relatively small, even for the high-precipitation scenarios, with an actual decrease in soil moisture when the temperature increased 4°C and precipitation increased 10%. During the winter months, percentage increases in precipitation have a larger effect on absolute precipitation than the same percentage increase in summer months simply because overall precipitation levels are higher. Yet these increases do not manifest themselves as proportional increases in winter soil moisture. There

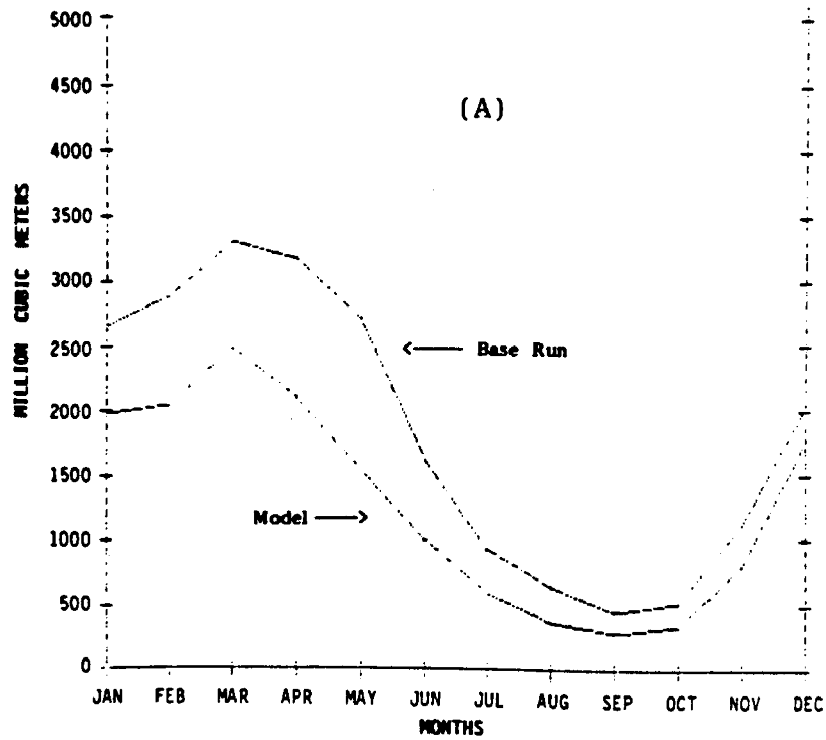

Figure 4a. Average Monthly Runoff (Model and Base Run) for the T+2°C, P-20% Scenario

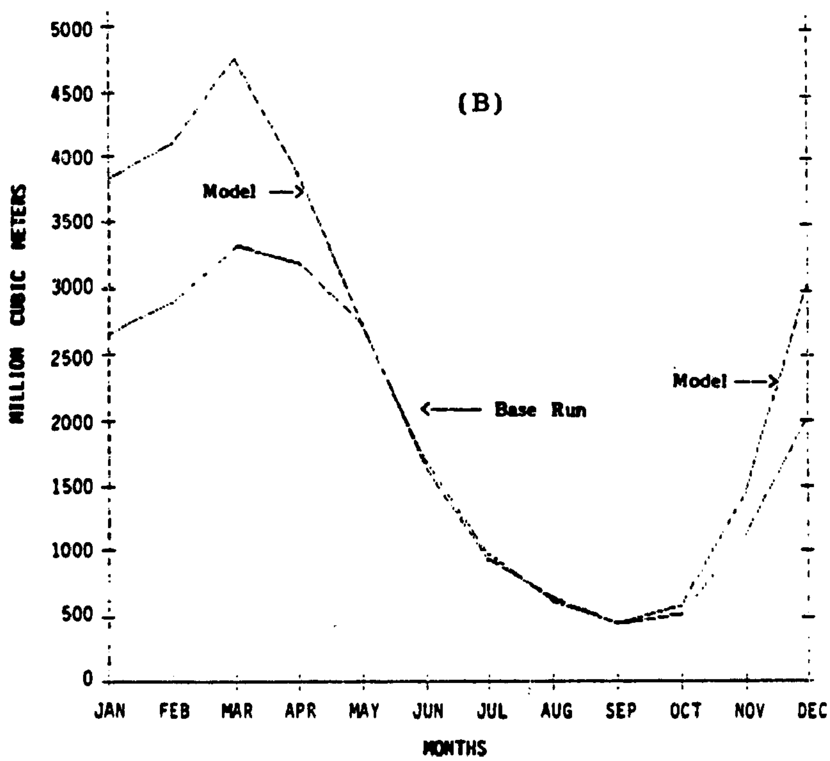

Figure 4b. Average Monthly Runoff (Model and Base Run) for the T+2°C, P+20% Scenario

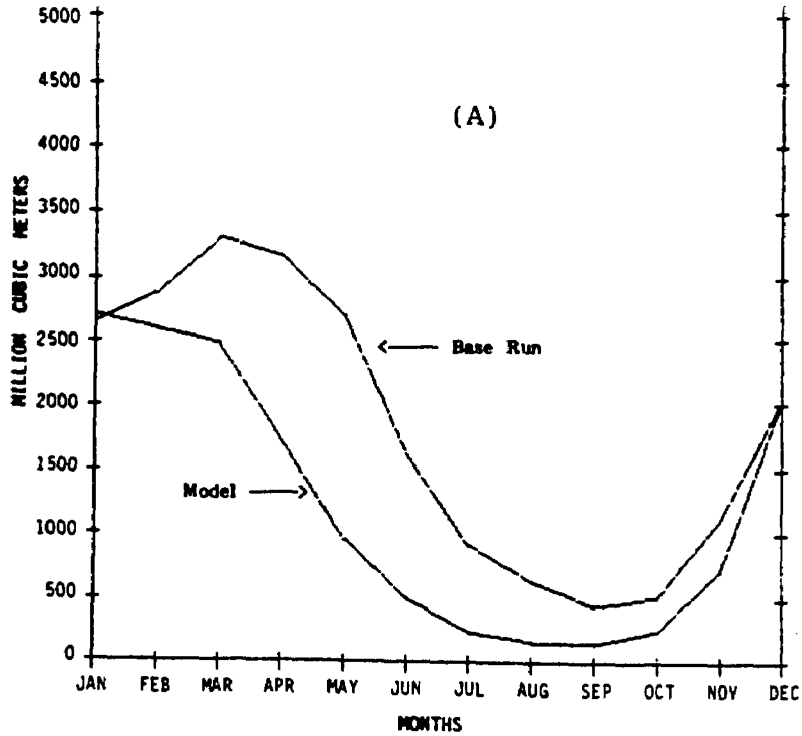

Figure 5a. Average Monthly Model and Base Runoff for the T+4°C, P-20% Scenario.

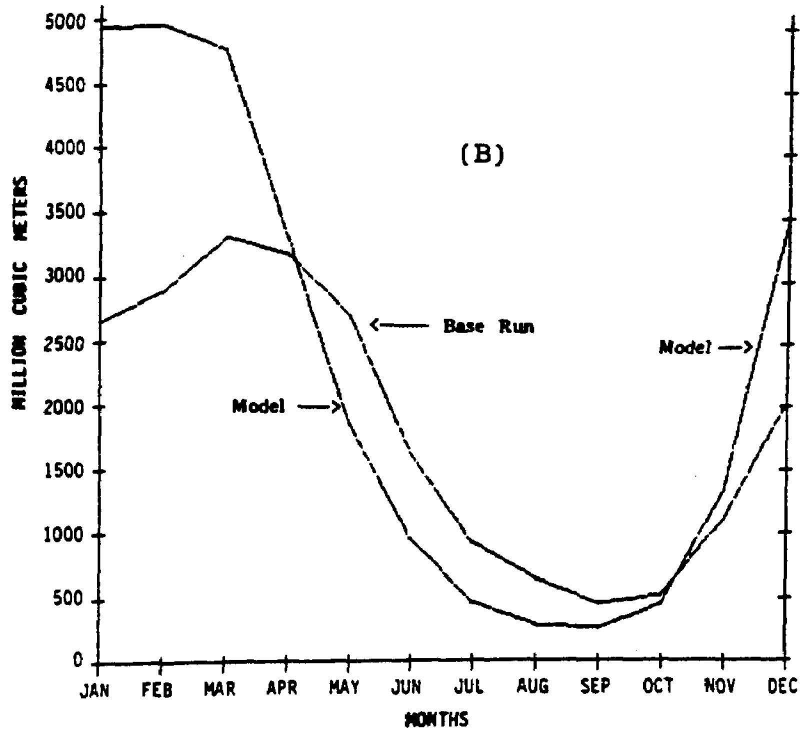

Figure 5b. Average Monthly Model and Base Runoff for the T+4°C, P+20% Scenario

Table 5. Effect of Hypothetical Temperature and Precipitation Scenarios on the Average Summer (JJA) Soil Moisture (Lower Basin)

(Percent Change over Base Run)

Precipitation Change / Temperature Change	-20%	-10%	0	+10%	+20%
T + 2°C	-28	-20	-16	-12	-8
T + 4°C	-44	-38	-33	-29	-26

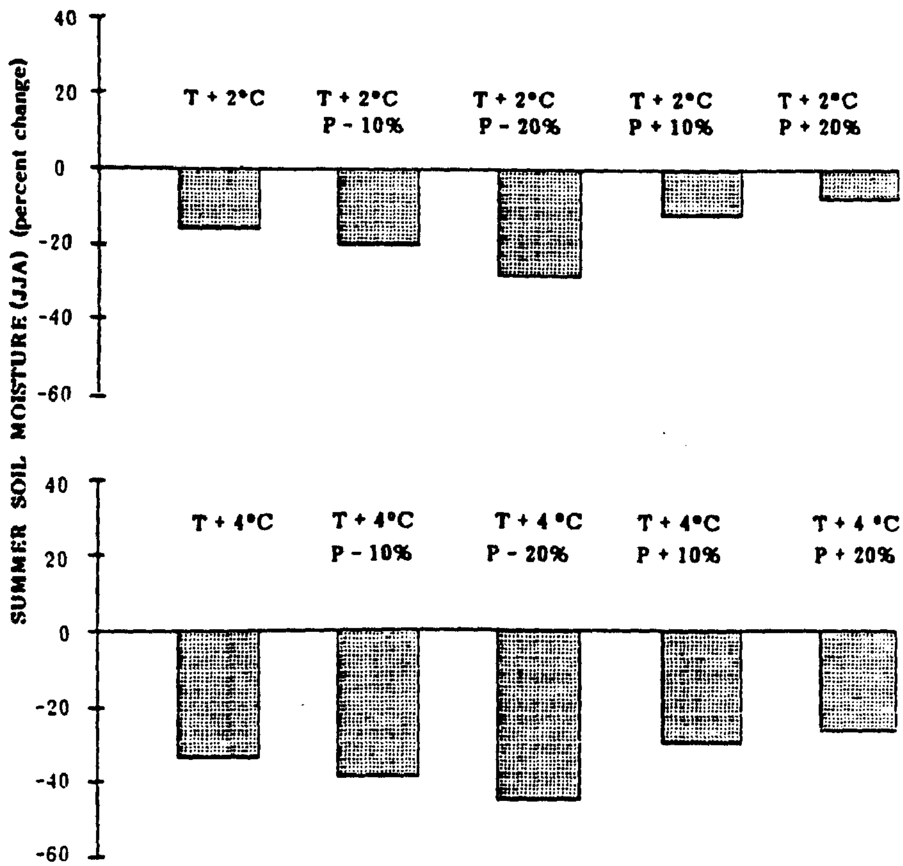

Figure 6. Percent Change in Average Summer (June, July, August) Soil Moisture for All Ten Hypothetical Scenarios

are two principal reasons for this: during the winter months, soils tend to be near or at saturation and surplus moisture runs off, and larger precipitation events in winter result in more prompt storm runoff, which does not become available to recharge soil moisture. Decreases in precipitation have the opposite effect, which can be seen by the larger proportional decreases in average winter soil-moisture values. Table 6 shows the percent changes in average winter soil-moisture values for the ten runs using hypothetical inputs. Unlike the summer soil-moisture results, precipitation changes are as effective as changes in temperatures in reducing average winter soil moisture. In this case, the lower winter temperatures have less of an effect on evapotranspiration rates, while the higher winter precipitation has a proportionally larger effect.

Table 6. Effect of Hypothetical Temperature and Precipitation Scenarios on the Average Winter (DJF) Soil Moisture (Lower Basin) (Percent Change over Base Run)

Precipitation Change / Temperature Change	-20%	-10%	0	+10%	+20%
T + 2°C	-20	-11	-4	+2	+ 6
T + 4°C	-25	-16	-9	-3	+ 3

Changes in Average Monthly Available Soil Moisture

The models imply that monthly soil-moisture availability in the Sacramento Basin using the hypothetical temperature and precipitation scenarios would be reduced consistently from its base level, with the greatest percentage reductions occurring during the summer months. For seven of the ten hypothetical cases, soil-moisture values were reduced in every month of the year. For the other three runs, which involve increases in monthly precipitation, only slight increases in the soil moisture during winter months were observed. Table 7 shows the average monthly soil moisture, the 50-year mean of the annual average soil-moisture values, and the percent changes between these values and the values from the base run for the lower basin.

This section has described the changes in seasonal and monthly soil moisture and runoff that result from using a series of hypothetical climate-change scenarios to drive the water-balance model. Many of these changes are persistent and significant, despite quite variable precipitation patterns. Among the most important changes noted are major, pervasive decreases in the average summer soil moisture and the volume of summer runoff, and large increases in the volume of winter runoff. The next section describes the results of using temperature and precipitation output from the eight GCM climate scenarios to drive the water-balance model.

GCM SCENARIOS

Each of the three GCM studies produce temperature and precipitation estimates for individual grid points under a doubled concentration of atmospheric carbon dioxide. These data were used to test the sensitivity of runoff and soil moisture in the study region in the same manner as the

Table 7. Effect of Hypothetical Temperature and Precipitation Scenarios on Average Monthly and Long-Term Annual Average Soil Moisture of the Lower Basin (Millimeters and Percent Change over Base Run)[1]

(Millimeters and Percent Change over Base Run)[1]

Run[2]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
BASE	195	226	233	217	170	110	61	36	25	29	77	142	127
T+2C	187	220	228	210	158	98	49	27	18	22	69	131	118
	-.04	-.03	-.02	-.03	-.07	-.11	-.19	-.24	-.28	-.24	-.10	-.08	-.07
T2P1	174	208	219	201	150	92	47	26	17	19	60	117	111
	-.11	-.08	-.06	-.07	-.12	-.16	-.24	-.28	-.32	-.33	-.23	-.18	-.13
T2P2	157	192	203	186	137	84	42	23	15	16	50	101	101
	-.20	-.15	-.13	-.14	-.19	-.24	-.30	-.35	-.39	-.43	-.35	-.29	-.21
T2P3	198	229	235	218	165	103	52	29	19	25	79	144	125
	.01	.02	.01	.00	-.03	-.07	-.15	-.20	-.25	-.14	.02	.02	-.02
T2P4	208	235	239	222	171	106	54	30	20	28	88	156	130
	.07	.04	.03	.02	.00	-.03	-.12	-.17	-.21	-.04	.15	.10	.02
T+4C	179	214	222	202	145	83	37	19	11	15	60	121	109
	-.08	-.05	-.05	-.07	-.14	-.24	-.39	-.48	-.54	-.49	-.23	-.15	-.14
T4P1	165	200	211	190	135	77	34	17	10	13	51	107	101
	-.16	-.11	-.10	-.12	-.20	-.30	-.44	-.53	-.58	-.57	-.34	-.25	-.20
T4P2	147	183	194	174	123	70	31	16	9	11	42	91	91
	-.24	-.19	-.17	-.20	-.28	-.37	-.49	-.57	-.63	-.64	-.45	-.36	-.28
T4P3	191	224	230	210	152	87	39	20	12	17	69	135	115
	-.02	-.01	-.01	-.03	-.10	-.21	-.36	-.46	-.52	-.41	-.11	-.05	-.09
T4P4	201	231	236	216	158	91	41	20	13	20	78	146	121
	.03	.02	.01	-.01	-.07	-.17	-.33	-.43	-.49	-.32	.01	.03	-.05

__Notes to Table 7.__

1. The decimal values on the lines __following__ each run are the percentage change in available soil moisture between the model run and the base run, or $(SM_{model} - SM_{base})/(SM_{base})$. Thus, average-January available soil moisture for the T + 2 degrees C ("T+2C") run decreased by 0.04, or 4 percent, over the base run ("Base"). Similarly, annual-average available soil moisture for the same run decreased by an average of 0.07, or 7 percent. Average-July available soil moisture for the T4P4 run (the last run in the table above) decreased by 0.33, or 33 percent, over the base run, while annual-average available soil moisture for this run decreased by an average of 5 percent.

2. Runs are coded as follows:

Base: Base run using historical temperature and precipitation.
T + 2C: Temperature increase of 2 degrees Celsius.
T2P1: T + 2 C; Precipitation decrease of 10 percent.
T2P2: T + 2 C; Precipitation decrease of 20 percent.
T2P3: T + 2 C; Precipitation increase of 10 percent.
T2P4: T + 2 C; Precipitation increase of 20 percent.
T + 4C: Temperature increase of 4 degrees Celsius.
T4P1: T + 4 C; Precipitation decrease of 10 percent.
T4P2: T + 4 C; Precipitation decrease of 20 percent.
T4P3: T + 4 C; Precipitation increase of 10 percent.
T4P4: T + 4 C; Precipitation increase of 20 percent.

hypothetical scenarios of the preceding section. Each of the three models was used to produce three different scenarios: predicted temperature changes alone; temperature changes together with the relative (percent) change in precipitation; and temperature changes together with the absolute change in precipitation. For reasons described in Gleick (1986b), the relative precipitation runs from the NCAR model were not included in the analysis. Table 7 summarizes the eight scenarios developed from the GCM temperature and precipitation data.

State-of-the-art GCMs provide us with one of our only direct insights into the behavior of global climate at hundreds of different points around the globe. As such, precipitation and temperature data from individual grid points can be used to develop additional climatic scenarios to evaluate the hydrologic response of regional watersheds to climate changes. These additional data provide a "sense" of realism that cannot be matched by even a wide range of hypothetical scenarios. In addition, as scientists continue to improve the spatial resolution and hydrologic parameterizations of GCMs, the quality of regional detail will improve. These improvements in regional output can then be used to drive water-balance evaluations of hydrologic areas of special interest and concern.

All three GCMs produced precipitation and temperature data for a control ($1xCO_2$) scenario and for a doubled CO_2 ($2xCO_2$) scenario. The differences in model formulations, parameterizations, grid scales, and geographical resolutions among the three GCMs result in differences in estimates of the effect of a doubled concentration of carbon dioxide on precipitation and temperature. Differences in the control runs--the attempt to reproduce existing climate--introduce further variations in the temperature and precipitation results.

The eight GCM scenarios were used to drive the water-balance model. The results are summarized here for two spatial resolutions: average seasonal runoff and average monthly runoff. Significant changes in runoff patterns are identified and discussed in the following sections.

Changes in Average Summer and Winter Runoff

Significant changes in seasonal runoff that are consistent across the different GCMs are observed in each of the scenarios. Despite differences in GCM resolutions, formulations, and parameterizations, the values of summer runoff predicted by the water-balance runs using GCM data all change in the same direction and by similar magnitudes; winter runoff shows similar effects in the opposite direction. Specifically, average summer runoff decreases significantly for all eight scenarios while average winter runoff increases in all eight scenarios. Tables 8 and 9 summarize the percentage changes in average summer and average winter runoff, respectively, for the eight GCM scenarios. When only the GCM temperature changes are evaluated, average summer runoff values decrease dramatically by 40% to 68%. These decreases persist when the precipitation changes are included, even under the spring and summer precipitation increases of the GISS model. All eight GCM scenarios show a major drop in summer runoff volumes, with a minimum decrease of 30% and a maximum decrease of 68% over the historical base run. Just as summer runoff decreases in all eight scenarios, winter runoff increases in all eight. The average winter runoff increases 16%-81%. The greatest increases occur with

Table 7. Effect of GCM Temperature and Precipitation Scenarios on the Average Summer (JJA) Runoff

(Percent Change over Base Run)

GCM [1]	T Only	T and Relative P	T and Absolute P
NCAR	-40	n.a.	-30
GFDL	-50	-48	-48
GISS	-68	-53	-40

1. The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.

n.a. Not included here; see Gleick (1986a, Appendix C).

Table 8. Effect of GCM Temperature and Precipitation Scenarios on the Average Winter (DJF) Runoff

(Percent Change over Base Run)

GCM [1]	T Only	T and Relative P	T and Absolute P
NCAR	+17	n.a.	+16
GFDL	+26	+34	+33
GISS	+38	+81	+66

1. The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.

n.a. Not included here; see Gleick (1986a, Appendix C).

the high precipitation scenarios of the GISS model. The magnitude of the average summer runoff decreases could be important to agriculture, while the large increases in average winter runoff suggest significant flooding and water-management problems. These runoff changes are plotted in Figures 7 and 8.

The consistency of these changes despite the variations in the GCM assumptions and outputs is the result of two major factors: the temperature increases in the models are driving significant changes in the timing of runoff during the year, and although the precipitation changes make significant contributions to the changes in the magnitude of runoff, they are less important in determining the timing of that runoff than are the changes in temperature.

Changes in Average Monthly Runoff

Water-balance runs using all eight GCM scenarios show increases in runoff during each of the winter months. These increases slowly give way to decreases in runoff during the spring and summer months with a minimum of runoff during late summer and early fall. The GCM temperature increases alone produce very large decreases in runoff during the summer months and large increases in runoff during January and February. As examples, Figures 9, 10, and 11 plot the average monthly model runoff produced for the three GCM temperature scenarios plotted against the average monthly runoff for the base run. The change in timing of runoff can be seen clearly in these plots. Although the overall change in annual runoff volumes for the different runs figures is large. Table 10 lists the data on average monthly runoff, average annual runoff, and the percentage changes for all eight of the GCM scenarios and the base and case run.

As with the hypothetical scenarios, the changes in the timing of runoff in the GCM-driven cases occur primarily because of the increase in average temperatures. Higher average temperatures cause a significant decrease in the proportion of winter precipitation that falls as snow and an earlier and shorter spring snowmelt. The first effect causes greater winter rainfall and runoff, since less overall precipitation enters the snowpack to be held over until spring melt. The second effect intensifies the magnitude of peak flows in spring and shortens the overall duration of spring runoff, which leads to decreases in summer runoff levels and depress soil-moisture levels throughout the spring and summer.

Among the most consistent and significant results obtained from this study are the decreases in soil-moisture availability during critical parts of the year. The next two sections describe the seasonal and monthly soil-moisture changes that result from using the GCM temperature and precipitation scenarios to drive the water-balance model of the Sacramento Basin. This section will focus primarily on the consequences of GCM-estimated changes in precipitation and temperature for available soil moisture in the agricultural areas of the Sacramento Basin.

Changes in Average Summer and Winter Available Soil Moisture

Water-balance model results using all eight GCM scenarios show significant reductions for the base case summer soil-moisture values in the

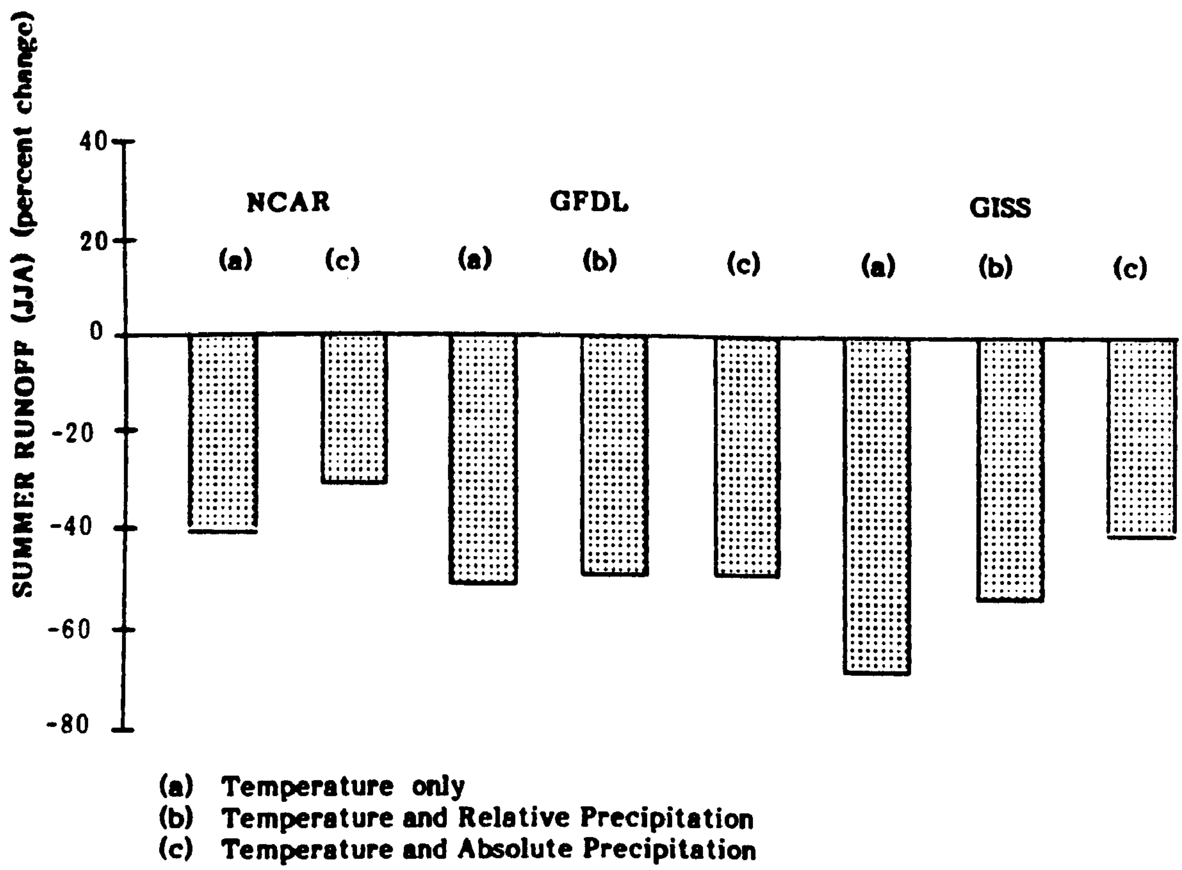

Figure 7. Percent Change in Average Summer (June, July, and August) Runoff for All Eight GCM Scenarios

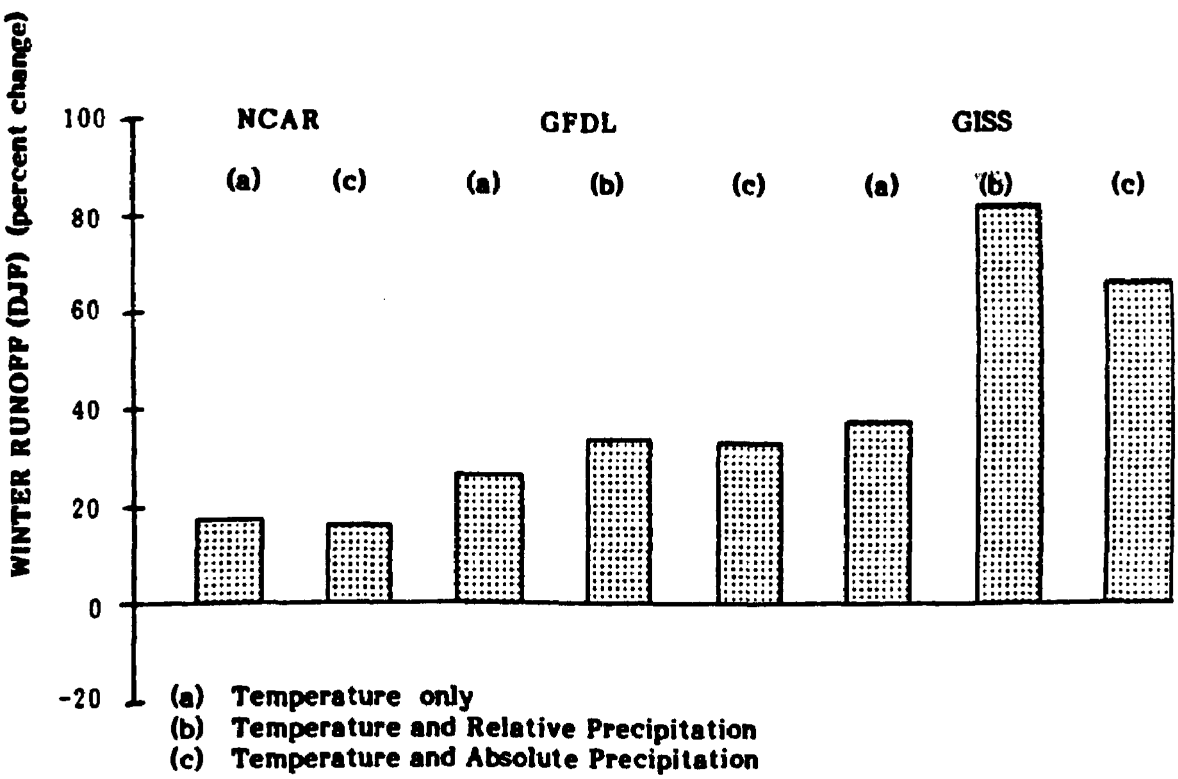

Figure 8. Percent Change in Average Winter (December, January, and February) Runoff for All Eight GCM Scenarios

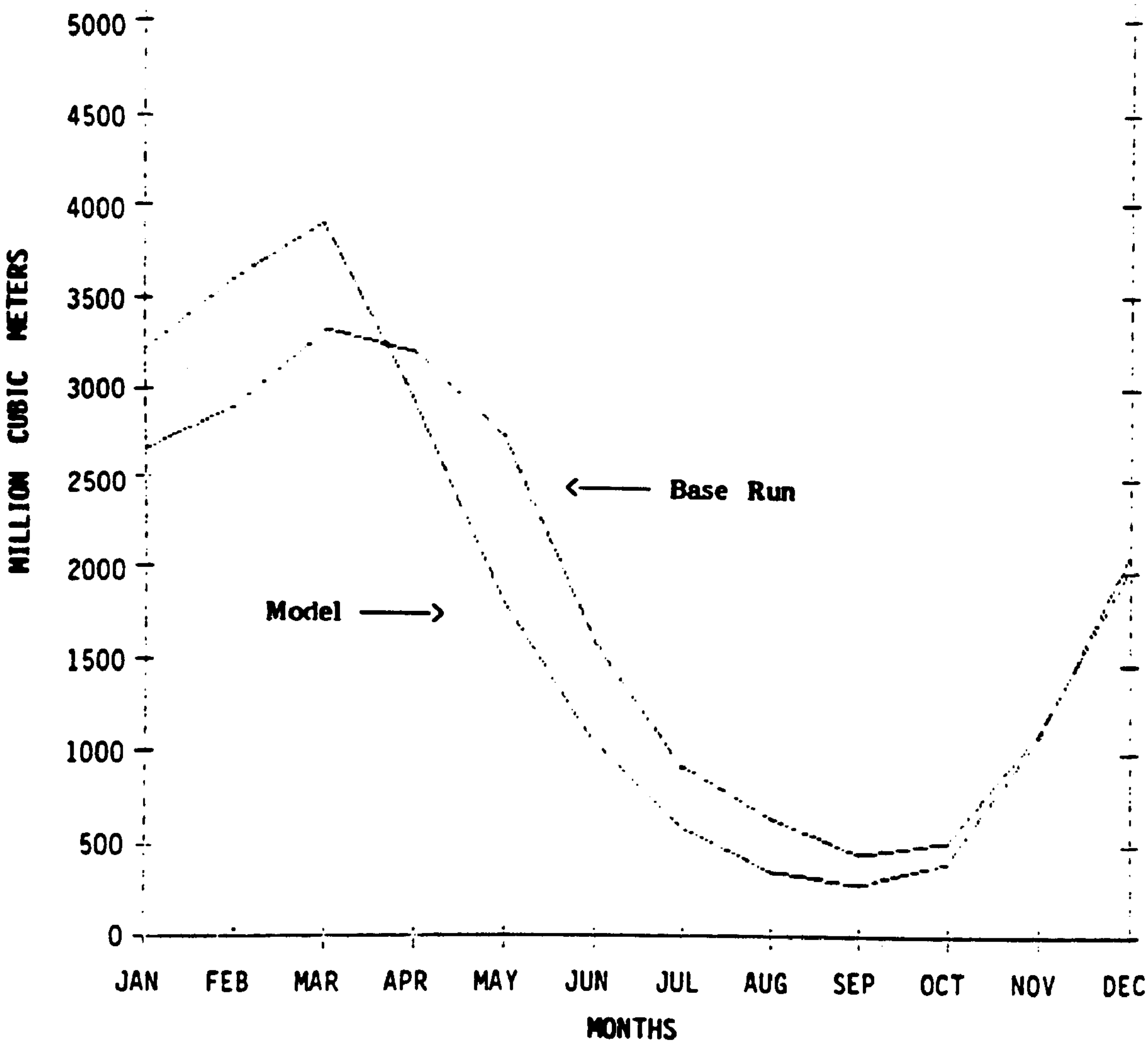

Figure 9. Average Monthly Model and Base Runoff for the NCAR Temperature Assumptions

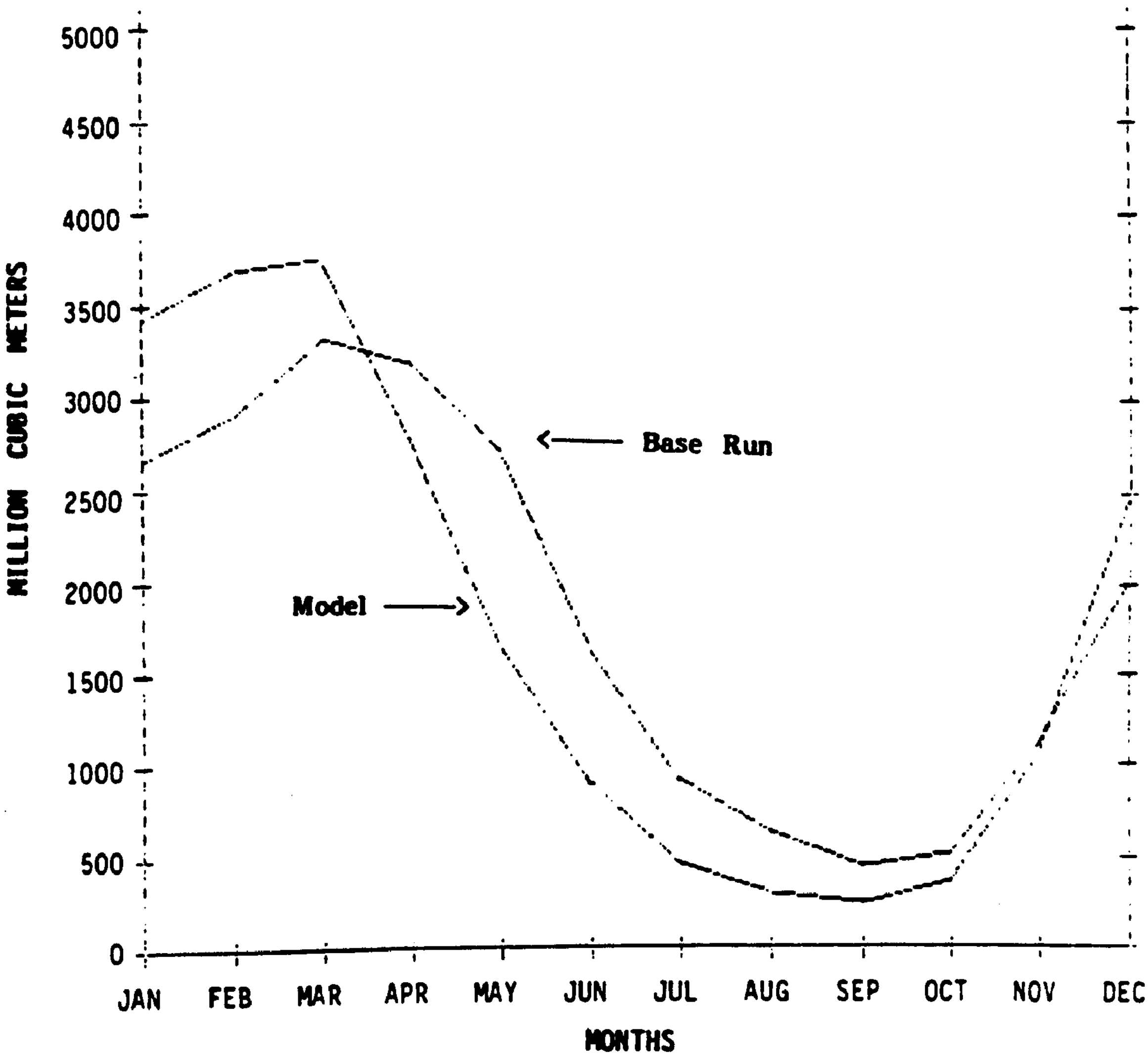

Figure 10. Average Monthly Model and Base Runoff for the GFDL Temperature Assumptions

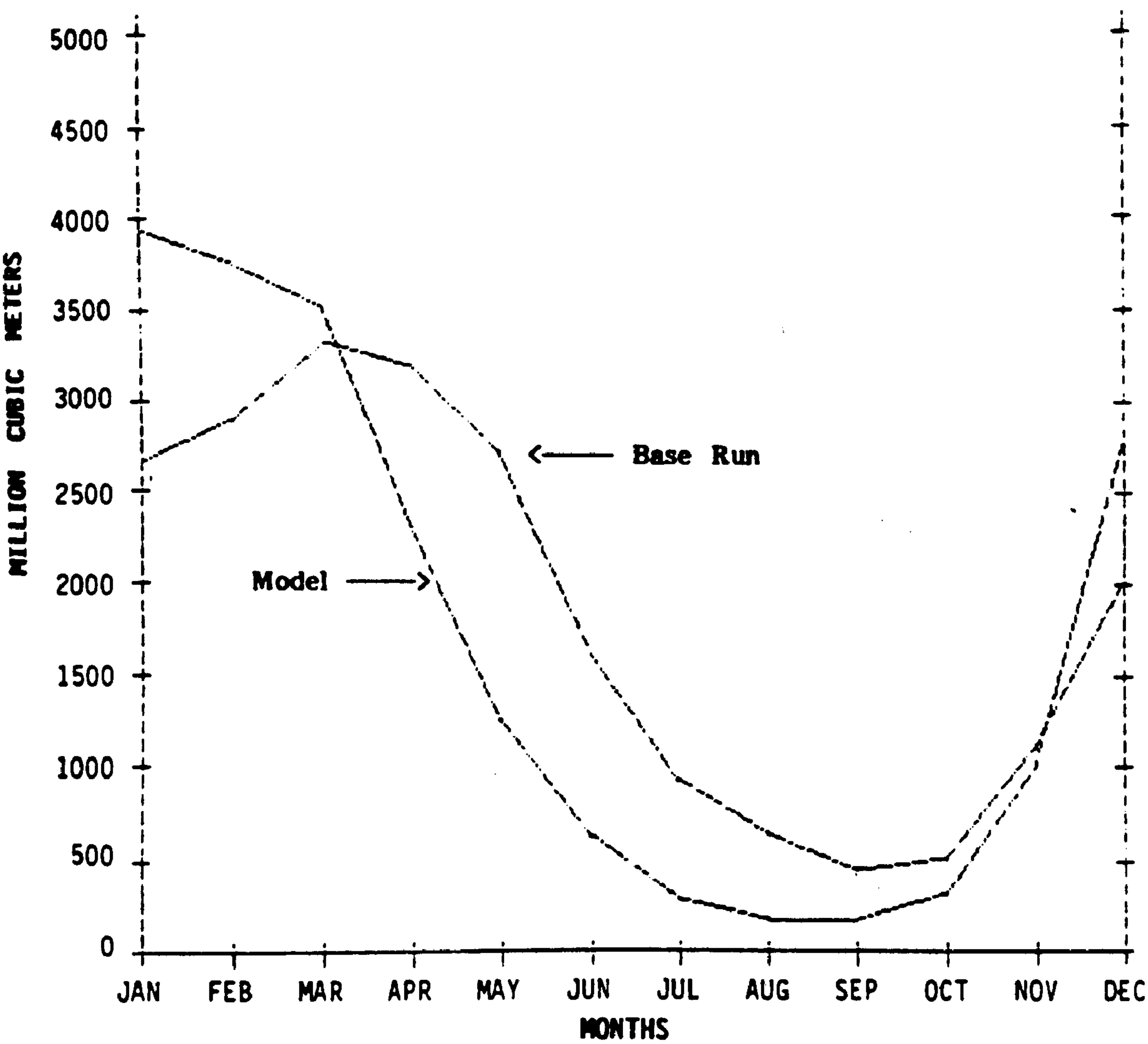

Figure 11. Average Monthly Model and Base Runoff for the GISS Temperature Assumptions

Table 10. Effect of GCM Temperature and Precipitation Scenarios on Average Monthly and Average Annual Runoff: A Summary

(1000 Acre-feet and Percent Change over Base Run)[1]

Run[2]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Base	2118	2245	2660	2481	1951	1285	773	492	348	401	882	1611	17245
National Center for Atmospheric Research (NCAR) GCM:													
T	2518	2824	3059	2291	1428	821	440	275	217	306	842	1646	16667
	.19	.26	.15	-.08	-.27	-.36	-.43	-.44	-.38	-.24	-.05	.02	-.03
T;P_a	3162	2318	3029	2278	1610	987	518	273	211	300	846	1429	16961
	.49	.03	.14	-.08	-.17	-.23	-.33	-.44	-.39	-.25	-.04	-.11	-.02
Geophysical Fluid Dynamics Laboratory (GFDL) GCM:													
T	2678	2887	2950	2181	1286	702	356	221	184	287	811	1944	16488
	.26	.29	.11	-.12	-.34	-.45	-.54	-.55	-.47	-.28	-.08	.21	-.04
T;P_r	3274	2847	2956	2044	1207	694	357	262	196	184	783	1876	16679
	.55	.27	.11	-.18	-.38	-.46	-.54	-.47	-.44	-.54	-.11	.16	-.03
T;P_a	3261	2816	2959	2071	1205	704	362	272	212	174	772	1858	16666
	.54	.25	.11	-.17	-.38	-.45	-.53	-.45	-.39	-.57	-.12	.15	-.03
Goddard Institute for Space Sciences (GISS) GCM:													
T	3100	2946	2745	1817	979	482	213	133	132	250	778	2183	15759
	.46	.31	.03	-.27	-.50	-.62	-.72	-.73	-.62	-.38	-.12	.36	-.09
T;P_r	4169	3878	4406	2499	1354	707	303	188	123	387	1263	2756	22033
	.97	.73	.66	.01	-.31	-.45	-.61	-.62	-.65	-.03	.43	.71	.28
T;P_a	3806	3579	3910	2307	1339	981	333	224	135	344	1135	2549	20642
	.80	.59	.47	-.07	-.31	-.24	-.57	-.54	-.61	-.14	.29	.58	.20

__Notes to Table 10.__

[Please note that the runoff values are given in acre-feet, the standard unit for runoff in all available U.S. databases. The conversion to cubic meters (m^3) is 1233 m^3 per acre-foot.]

1. The decimal values on the lines __following__ each run are the percentage change in runoff between the model run and the base run, or $(RO_{model} - RO_{base})/(RO_{base})$. Thus, average-January runoff for the NCAR Temperature-only run ("T") run increased by 0.19, or 19 percent, over the base run ("Base"). Similarly, average-annual runoff for the same run decreased by 0.03, or 3 percent. Average-January runoff for the GISS Temperature and absolute precipitation run (the last run in the table above) increased by 0.80, or 80 percent, over the base run, while average-annual runoff for this run increased by 20 percent.

2. Runs are coded as follows:

T: Temperature changes only.
T;P_r: Temperature changes and relative precipitation changes.
T;P_a: Temperature changes and absolute precipitation changes.

(See text for details of these runs.)

lower basin. These reductions range 14-36%. In six of the eight scenarios, average winter soil-moisture values undergo modest reductions of 2-10%, while the remaining two runs show a 3% and 4% increase in soil moisture. Table 11 and Figure 12 present the changes in average summer soil moisture based on the GCM climate-change scenarios; Table 12 presents the changes in average winter soil moisture.

The decreases in average summer soil moisture in the Sacramento Basin are remarkably consistent regardless of which GCM scenario is used to drive the water-balance model. Soil-moisture losses of between 20% and 40% result from seven of the eight scenarios, with the remaining decrease of 14% occurring in the GISS high-precipitation case.

The magnitude and the consistency of the average summer soil-moisture drying signify a major hydrologic impact, especially given that these results are consistent with the summer soil-moisture results from the ten hypothetical temperature and precipitation scenarios discussed earlier: <u>all eighteen climate-change scenarios yield large losses of summer soil moisture when used to drive the water-balance model</u>.

<u>Changes in Average Monthly Available Soil Moisture</u>

There is a consistent monthly depression of soil-moisture availability for the GCM runs, with the exception of slight increases during some winter months for the highest precipitation scenarios of the GISS model. The water-balance model results using six of the eight GCM scenarios show decreases in monthly soil moisture after March continuing through December. The other two scenarios, using the GISS relative and absolute precipitation data, show increases in soil moisture beginning again in November. Table 13 summarizes the average monthly soil moisture and the 50-year mean of the annual average soil-moisture results for the lower basin.

RESULT HIGHLIGHTS AND DISCUSSION

Eighteen climate-change scenarios were used to drive a water-balance model designed to evaluate the impacts of global climatic changes on runoff and soil moisture in a major watershed. The scenarios included ten scenarios with hypothetical increases and decreases in precipitation and temperature and eight scenarios with changes in precipitation and temperature generated using results from three state-of-the-art general circulation models of global climate. The results from using these eighteen temperature and precipitation scenarios to drive the water-balance model show some consistent and pervasive changes in both runoff and soil moisture, despite the fact that the scenarios have some major difference among them.

The results of the water-balance runs show that dramatic shifts will occur in the timing and distribution of both soil moisture and runoff. The directions of these shifts are independent of the level of rainfall, while the magnitudes of the soil moisture and runoff changes are exacerbated by increases or decreases in precipitation. Four particularly important and consistent changes were observed:

- Large decreases in summer soil-moisture levels for all eighteen climate-change scenarios

Table 11. Effect of GCM Temperature and Precipitation Scenarios on the Average Summer (JJA) Soil Moisture (Lower Basin)

(Percent Change over Base Run) [1]

GCM [1]	T Only	T and Relative P	T and Absolute P
NCAR	-28	n.a.	-20
GFDL	-33	-35	-36
GISS	-31	-24	-14

1. The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.

n.a. Not included here; see Gleick (1986a, Appendix C).

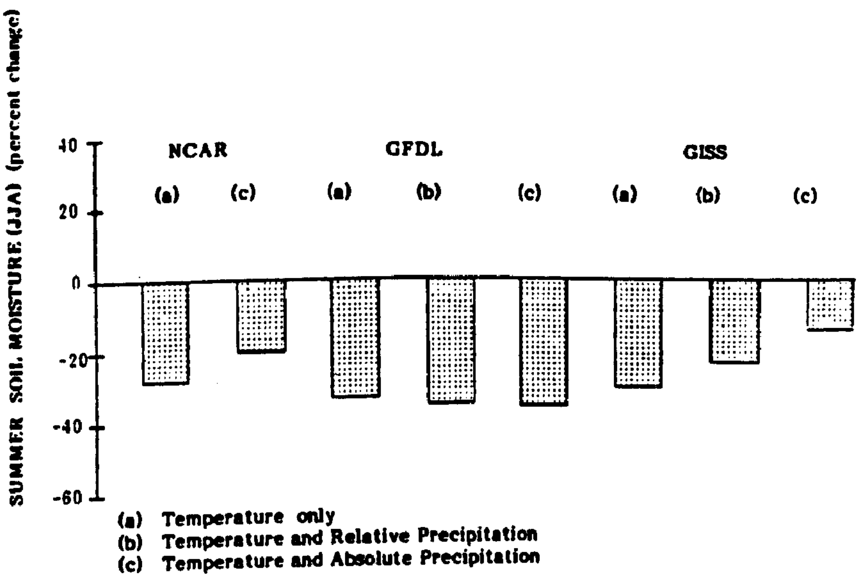

Figure 12. Percent Change in Average Summer Soil Moisture (June, July, and August) Over the Base Run for All Eight GCM Scenarios. (Note the consistent decreases in summer soil moisture.)

Table 12. Effect of GCM Temperature and Precipitation Scenarios on the Average Winter (DJF) Soil Moisture (Lower Basin)

(Percent Change over Base Run)

GCM [1]	T Only	T and Relative P	T and Absolute P
NCAR	-2	n.a.	-3
GFDL	-5	-4	-3
GISS	-10.	+4	+3

1. The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.

n.a. Not included here; see Gleick (1986a, Appendix C).

- Decreases in summer runoff volumes for all eighteen climate-change scenarios
- Major shifts in the timing of average monthly runoff throughout the years, with spring and summer runoff shifting to winter
- Large increases in winter runoff volumes for fifteen of the eighteen climate-change scenarios, including all eight GCM cases. The other three scenarios--all of which involved 10% or 20% decreases in precipitation--showed small or moderate decreases in winter runoff.

The hydrologic changes described above will have serious implications for many aspects of water resources, including agricultural water supply, flooding and drought probabilities, groundwater use and recharge, and reservoir design and operation--to name only a few. Only by looking at the specific characteristics of water-resource problems, and their vulnerability to the types of changes in runoff and soil moisture identified above, can details of future societal impacts be evaluated. Such evaluations must begin now in diverse hydrologic basins so that policies for mitigating or preventing the most serious hydrologic impacts of climatic changes can be developed and implemented.

Table 13. Effect of GCM Temperature and Precipitation Scenarios on Average Monthly and Long-Term Annual Average Soil Moisture of the Lower Basin

(Millimeters and Percent Change over Base Run)[1]

Run[2]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
BASE	195	226	233	217	170	110	61	36	25	29	77	142	127
National Center for Atmospheric Research (NCAR) GCM:													
T	191	222	229	204	144	90	38	21	13	18	72	137	115
	-.02	-.02	-.02	-.06	-.15	-.18	-.38	-.43	-.46	-.38	-.07	-.04	-.09
$T;P_a$	202	217	229	204	152	100	43	23	15	19	73	127	117
	.04	-.04	-.02	-.06	-.11	-.09	-.30	-.36	-.40	-.34	-.05	-.11	-.08
Geophysical Fluid Dynamics Laboratory (GFDL) GCM:													
T	185	218	227	207	152	82	37	20	12	17	66	129	113
	-.05	-.03	-.03	-.05	-.11	-.26	-.39	-.46	-.50	-.40	-.15	-.09	-.11
$T;P_r$	194	220	227	204	147	79	36	19	12	12	63	126	112
	-.01	-.03	-.03	-.06	-.13	-.28	-.41	-.47	-.51	-.59	-.18	-.11	-.12
$T;P_a$	198	222	228	204	145	78	36	19	12	13	64	127	112
	.02	-.02	-.02	-.06	-.15	-.29	-.41	-.47	-.52	-.55	-.17	-.11	-.12
Goddard Institute for Space Sciences (GISS) GCM:													
T	175	210	219	197	149	86	40	17	8	11	60	122	108
	-.10	-.07	-.06	-.09	-.13	-.22	-.35	-.52	-.67	-.61	-.22	-.14	-.15
$T;P_r$	202	230	238	210	161	94	44	19	9	18	94	152	123
	.03	.02	.02	-.03	-.05	-.14	-.29	-.47	-.63	-.36	.22	.07	-.03
$T;P_a$	201	231	241	213	167	107	50	22	11	15	84	148	124
	.03	.02	.03	-.02	-.02	-.03	-.18	-.39	-.56	-.48	.09	.04	-.02

Notes to Table 13.

1. The decimal values on the lines following each run are the percentage change in available soil moisture between the model run and the base run, or $(SM_{model} - SM_{base})/(SM_{base})$. Thus, average-June available soil moisture for the NCAR Temperature ("T") run decreased by 0.18, or 18 percent, over the base run ("Base"). Similarly, annual-average available soil moisture for the same run decreased by an average of 0.09, or 9 percent. Average-July available soil moisture for the GISS Temperature and absolute precipitation run ($T;P_a$) run (the last run in the table above) decreased by 0.18, or 18 percent, over the base run, while annual-average available soil moisture for this run decreased by an average of 2 percent.

2. Runs are coded as follows:

T: Temperature changes only.

$T;P_r$: Temperature changes and relative precipitation changes.

$T;P_a$: Temperature changes and absolute precipitation changes.

(See text for details of these runs.)

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Hydrologic Consequences of Increases in Trace Gases and CO_2 in the Atmosphere

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INTRODUCTION

There has been much speculation concerning the effect of increasing atmospheric CO_2 and other trace gases on all aspects of life on this planet. Most investigators agree that such increases will result in some warming of the lower layers of the atmosphere. However, whether ice caps will melt or grow; whether sea levels will rise; whether agriculture will just move poleward uniformly; whether there will be local adjustments in the global circulation patterns; whether precipitation will change as a result of increased evapotranspiration; and how all these possible changes will influence socioeconomic factors, our standard of living, or our quality of life are questions subject to endless debate and speculation. Clearly, one reason for our inability to definitively answer these questions lies in our lack of reliable information on the magnitude of changes in temperature and precipitation to expect as greenhouse gases increase. However, even if reliable climatic data were available, uncertainties would still exist because of the difficulty in determining how particular climatic conditions influence such factors as agricultural markets, human perceptions and tastes, water demands and supplies, or even political and economic decisions. We can only continue to work toward a more accurate understanding of future climatic conditions while, at the same time, trying to translate those climatic conditions into more useful human, economic, physical, or political responses through the application of meaningful models.

We have a well-tested model that expresses how atmospheric energy (expressed as air temperature) and precipitation influence the water relations of a place or area. The climatic water budget, originally developed by Thornthwaite in the early 1940s and later modified by Thornthwaite and Mather (1955), has been used extensively to provide information on factors such as soil moisture storage, actual evapotranspiration, water deficit, soil water surplus, water runoff or streamflow, and snow storage and melt. Where checks are possible, the simple water budget bookkeeping procedure developed by

Thornthwaite and Mather has been found to provide reliable data for many parts of the world. Annual values of water surplus computed from the basic data of monthly temperature and precipitation approximate closely measured values of streamflow. In fact, Mather (1981) even suggested the use of the climatically computed values of surplus as a way to evaluate the accuracy of stream gaging stations. Values of computed soil moisture storage agree almost exactly with values of soil moisture content measured by the weighing and drying of soil samples (Thornthwaite and Mather 1955). Finally, many studies show that water deficit or the ratio of actual evapotranspiration to potential evapotranspiration is closely related to agricultural yields (Mather 1978).

Evaluation of the water budget bookkeeping method reveals that if precipitation increases in an area with no change in temperature (a surrogate for potential evapotranspiration) or with a decrease in temperature, an increase occurs in soil moisture storage and in stream runoff. An increase in precipitation accompanied by an increase in temperature is more difficult to evaluate because the relative magnitudes of these changes would determine whether soil moisture content and streamflow increase or decrease. If precipitation increases more than the climatic water demand, streamflow should increase, while if water demand, as a result of the atmospheric warming, exceeds the increase in precipitation, soil moisture and streamflow would decrease. Conversely, a precipitation decrease accompanied by an increase in climatic demand for water (temperature) should result in a decrease in soil moisture storage and streamflow. Clearly, the seasonal patterns of these changes would strongly influence the actual pattern of increase or decrease in soil moisture conditions or water surplus.

A number of investigators have used different water budgeting procedures to evaluate the effect of predicted temperature and precipitation changes resulting from increases in trace gases and atmospheric CO_2. Most of the predictions of climatic changes come from the operation of global circulation models under current and increased CO_2 conditions. These models, based on different assumptions concerning such factors as cloud cover, surface roughness, land-water distributions, oceanic influences, atmospheric water vapor, and surface-boundary layer exchanges, provide estimates of temperature and precipitation for present and various future scenarios. In this paper, we apply the temperature and precipitation data obtained from two of these global circulation models, the Goddard (GISS) model and the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) model, to the climatic water budget to determine the possible influence of predicted changes in temperature and precipitation on such factors as soil moisture deficit, water surplus, and soil moisture storage in twelve selected regions of the globe. The results not only suggest the complex nature of changes in hydrologic factors that will accompany an increase in CO_2 and other gases, but also reveal some of the difficulties in trying to draw conclusions from such modeled data.

Any attempt to understand future hydrologic conditions through the application of temperature and precipitation data derived from one of the global circulation models is fraught with uncertainties that the user must fully recognize. First, there is no reason to expect that future climates will merely repeat past conditions. One cannot necessarily look at warm episodes in the past period of instrumental records to model future climatic conditions resulting from increased CO_2. The reasons for the past climatic changes are different and there is every reason to expect that the pattern of climatic changes will also be different. Second, while investigators expect that the predicted increase in trace gases and CO_2 will lead to increases in atmospheric temperatures, there is some question concerning the timing and magnitude of the greenhouse warming. The influence of such climatic warming on precipitation is more in doubt since a number of feedback relations must also be considered. Third, the available models do not explain present conditions with great accuracy; built-in errors might produce even greater errors under future scenarios. Fourth, available global circulation models provide information for a rather coarse gridwork of points. The GISS model uses an 8° x 10° latitude and longitude grid while the GFDL model uses 4° x 5° grid. These networks cover a wide range of conditions. Topography can vary from coastal plains to mountains, while present climatic conditions might vary from desert to rainforest. Evaluating conditions at one spot in the grid can provide only rough estimates of what to expect in other parts of the grid area, and point estimates might not represent the whole grid.

BACKGROUND

Possibly the most active workers in the field of modeling the hydrologic effect of CO_2 warming have been Manabe and his associates at the NOAA Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. They have developed their own global circulation model (the NOAA/GFDL model), which they are continually improving and modifying, to provide a closer representation of real world conditions. Manabe and Wetherald (1980) used a simple version of a global circulation model to outline the global pattern of soil moisture. They suggested that there would be a high latitude region where the rate of runoff would increase appreciably along with a zonal belt of decreasing soil moisture at slightly lower latitudes. There would be regions of increased soil moisture along the east coast of the subtropical portion of the continent. The warming of the atmosphere predicted by the model would encourage the penetration of moist air into high latitudes and result in large increases in precipitation there.

Manabe, Wetherald, and Stouffer (1981) conducted a detailed analysis of three different circulation models: the S15, the G15, and the G21. The original S15 model was an idealized section of land and water stretching from pole to pole. It was 120° wide at the equator (60° land, 60° water) with a zonal wave number of the retained spectral components of 15. G15 had a global computational domain and more realistic geography with continents and oceans; the G21 was very similar to G15, except that it had a maximum zonal wave number of 21. The paper showed that the zonal mean value of soil moisture reduces appreciably in summer in two distinct zones in middle and high latitudes in response to the modeled increase in atmospheric CO_2. The authors concluded that the summer dryness resulted not only from the earlier ending of the snowmelt season, but also from the earlier occurrence of the spring to summer reduction in rainfall rate. The effect on the snowmelt season was more significant in high latitudes, while the reduction in rainfall rates was more important in middle latitudes. Results indicated a statistically significant increase in both soil moisture and rate of runoff in high latitudes in all models during all of the annual cycle with the exception of the summer.

The authors pointed out that the G15 and G21 models have a somewhat poor record of simulating current summer season precipitation (in comparison with the winter season precipitation). Further, the G21 model locates the tropical rainbelt over the tropical Atlantic and Pacific Oceans south of the equator, which does not correspond to currently observed patterns. The inability of the models to simulate current conditions raises certain questions about simulating double CO_2 conditions as well. The tropical rainbelt problem may be related to the abnormally high sea surface temperatures over the tropical Southern Hemisphere oceans in the G21 model.

Along with the enhanced poleward moisture transport, a CO_2-induced summer dryness appears in middle latitudes. This results from the poleward movement of the subtropical dry zone by about 5° latitude during summer. At this time, zonal mean soil moisture is reduced from 20% to 60% around 50° latitude and from 10% to 40% around 70° latitude. The percentage increase in zonal mean soil moisture which is found in high latitudes in all seasons except summer is of the order of 60%. These changes were found assuming a quadrupling of CO_2 concentrations rather than the more conventional doubling of CO_2.

In a recent analysis of this same problem of summer soil moisture conditions on a worldwide basis, Manabe and Wetherald (Volume 1) achieve essentially the same conclusions using a model that includes predicted cloud cover conditions. They find that the increased carbon dioxide conditions result in a reduction in soil moisture in summer over large regions in middle and high latitudes (the North American Great Plains, western Europe, northern Canada, and Siberia). There is also a winter enhancement of soil moisture over large midcontinent and high latitude land areas. While the authors question some of the details of the climatic changes that would accompany an increase in CO_2, they believe that the basic conclusions of the paper would remain unchanged by any imperfections in the model.

METHODOLOGY

Monthly temperature and precipitation data for twelve selected regions of the world were obtained from data tapes of the GISS and NOAA general circulation models. Two different analyses were applied to each set of data. First, the data of estimated monthly temperature and precipitation that would occur with a doubling of CO_2 in the atmosphere, as well as the actual modeled data of temperature and precipitation for current conditions (the "control" data), were entered into the climatic water budget; and values of the factors of the water budget were obtained from both sets of data. Differences in such factors as potential evapotranspiration, precipitation, water deficit, and water surplus were obtained by subtracting the control water budget factors from those obtained from the double CO_2 temperature and precipitation data. Second, since the models do not predict current conditions with great accuracy, we felt that a more reliable estimate might be obtained by applying information on the changes in monthly temperature and precipitation obtained from the differences between double CO_2 conditions and control conditions to current station conditions as actually measured. The Center for Climatic Research not only possesses one of the most extensive collections of monthly temperature and precipitation data from stations in all parts of the world, but it has also used those data to provide computer-generated climatic water budgets for each degree of latitude and longitude for all the land areas of the earth. Information on the actual change in monthly temperature from the control conditions to the double CO_2 conditions was applied to the presently available data on station temperatures within each selected region. Similarly, the percentage change in precipitation between the modeled control conditions and the doubled CO_2 conditions was determined and the present observed precipitation values were adjusted by these percentages to obtain new precipitation values for a CO_2 doubling. As in the previous case, the differences between water budget factors obtained from the modified current data and the actual current data were evaluated. Thus, four different estimates of the effect of doubling CO_2 on factors of the climatic water budget were considered. The four estimates may be summarized as follows:

- GISS model: Change in T, percent change in P applied to current measured data minus current data
- GISS model: Doubled CO_2 estimated conditions minus modeled control conditions
- NOAA model: Change in T, percent change in P applied to current measured data minus current data
- NOAA model: Doubled CO_2 estimated conditions minus modeled control conditions.

RESULTS

Tables 1-4 indicate the water budget results for the region in North America covering southeastern Texas and northern Mexico. The area studied is a rectangular geographical region ranging in size from 10°-15° of longitude and 13°-15° of latitude depending on the model being evaluated. Data on temperature and precipitation at a number of selected grid points within the area were obtained either from our own file of current data or from the evaluation of the GISS or NOAA global circulation models under control conditions and double CO_2 conditions.

Table 1 compares data from our current data files (shown in the lower portion) with data obtained by correcting the current data by the change in temperature and percentage change in precipitation between a double CO_2 event and the control situation (the model evaluation of a single CO_2 situation) using the GISS model (shown in the upper portion). The amount of water that can be held in the root zone at field capacity is considered to be 150 mm and water is withdrawn from the soil according to a linear declining availability model. Using present data, average annual potential evapotranspiration is found to equal 885 mm in the area with the monthly amounts ranging from 13 mm of potential evapotranspiration in January to 154 mm in July. Annual precipitation totals 707 mm over the whole area with a maximum value of 105 mm in July and a minimum value of 22 mm in January. Values greater than 50 mm occur each month from April through October and again in December. Soil moisture storage does not reach field capacity during the year on the average with highest values equal to 60 mm of storage in March. No water is found in the root zone from July through November. As a result of these dry conditions, a water deficit of 178 mm exists in the area with the period of deficit running from April through October. No surplus of water can occur since the soil moisture storage never returns to field capacity.

Under the computations adjusted for the change in temperature and precipitation resulting from a CO_2 doubling, annual potential evapotranspiration increases to 1150 mm while precipitation decreases to 692 mm. Peak

Table 1. Average Climatic Water Budget Data Over Texas-Mexico Region Using GISS Model, 150 mm Storage at Field Capacity, and Linear Declining Availability of Soil Moisture

GISS model.
Current data modified by change in T and percent change in P.

Month	T	APE	Prec	St	AE	Def	Surp
J	12.3	18	15	23	17	1	0
F	12.6	18	30	34	18	0	0
M	17.2	47	27	20	41	6	0
A	21.5	86	49	5	64	23	0
M	23.5	118	82	1	86	32	0
J	28.7	181	57	0	58	124	0
J	30.1	196	99	0	99	97	0
A	30.4	188	104	0	104	84	0
S	26.2	134	122	0	122	12	0
O	23.3	95	41	0	41	55	0
N	18.0	45	19	0	19	26	0
D	14.0	24	48	24	24	0	0
Yearly totals:		1150	692		692	458	0

GISS model area. Average current data.

Month	T	APE	Prec	St	AE	Def	Surp
J	7.7	13	22	46	13	0	0
F	8.8	16	28	59	16	0	0
M	12.5	35	37	60	35	0	0
A	16.9	64	50	48	63	1	0
M	20.7	101	71	24	95	6	0
J	24.6	138	71	2	92	46	0
J	25.9	154	105	0	106	48	0
A	25.8	145	94	0	94	51	0
S	23.0	106	94	0	94	12	0
O	18.1	66	52	0	52	13	0
N	12.9	32	32	0	32	0	0
D	8.2	16	14	37	37	14	0
Yearly totals:		885	707		707	178	0

Table 2. Average Climatic Water Budget Data Over Texas-Mexico Region Using NOAA Model, 150 mm Storage at Field Capacity, and Linear Declining Availability of Soil Moisture

NOAA model.
Current data modified by change in T and percent change in P.

Month	T	APE	Prec	St	AE	Def	Surp
J	15.7	26	22	3	23	3	0
F	17.9	37	21	2	23	14	0
M	18.6	49	39	1	40	9	0
A	21.8	81	26	0	26	55	0
M	25.3	138	107	0	107	31	0
J	30.6	193	63	0	63	130	0
J	30.9	199	66	0	66	133	0
A	30.4	186	93	0	93	93	0
S	31.8	176	21	0	21	154	0
O	26.5	132	55	0	55	77	0
N	18.4	41	21	0	21	20	0
D	14.9	22	25	4	22	0	0
Yearly totals:		1281	560		560	721	0

NOAA model area. Average current data.

Month	T	APE	Prec	St	AE	Def	Surp
J	10.1	18	24	19	18	0	0
F	11.7	23	23	20	23	0	0
M	14.9	44	22	9	32	12	0
A	18.8	73	36	2	43	30	0
M	22.2	111	62	0	64	47	0
J	25.6	146	77	0	77	69	0
J	25.9	152	86	0	86	67	0
A	25.7	143	79	0	79	64	0
S	23.4	107	89	0	89	18	0
O	19.3	70	51	0	51	19	0
N	13.9	33	34	1	33	0	0
D	10.3	18	31	13	18	0	0
Yearly totals:		939	613		613	326	0

Table 3. Average Climatic Water Budget Data Over Texas-Mexico Region Using GISS Model, 150 mm Storage at Field Capacity, and Linear Declining Availability of Soil Moisture

GISS model. Doubled CO_2 data.

Month	T	APE	Prec	St	AE	Def	Surp
J	10.3	18	67	143	18	0	0
F	11.1	20	91	150	20	0	64
M	14.5	41	83	150	41	0	42
A	20.1	83	88	150	83	0	5
M	21.2	101	134	150	101	0	32
J	24.0	130	125	146	130	0	0
J	25.7	152	162	150	152	0	6
A	26.1	148	145	147	148	0	0
S	25.6	128	72	92	128	0	0
O	20.8	80	37	50	78	2	0
N	14.6	35	38	53	35	0	0
D	11.5	22	63	94	22	0	0
Yearly totals:		957	1105		955	2	150

GISS model area. Control run data.

Month	T	APE	Prec	St	AE	Def	Surp
J	5.7	12	99	150	12	0	87
F	7.3	17	88	150	17	0	71
M	9.8	31	115	150	31	0	83
A	15.5	65	90	150	65	0	25
M	18.4	92	115	150	92	0	23
J	19.9	103	155	150	103	0	52
J	21.5	118	171	150	118	0	53
A	21.5	112	133	150	112	0	21
S	22.3	106	55	100	106	0	0
O	15.6	59	47	88	59	0	0
N	9.4	25	63	126	25	0	0
D	5.7	12	66	150	12	0	30
Yearly totals:		752	1197		752	0	445

Table 4. Average Climatic Water Budget Data Over Texas-Mexico Region Using NOAA Model, 150 mm Storage at Field Capacity, and Linear Declining Availability of Soil Moisture

NOAA model. Doubled CO_2 data.

Month	T	APE	Prec	St	AE	Def	Surp
J	9.9	7	95	150	7	0	83
F	14.2	18	103	150	18	0	85
M	16.9	36	115	150	36	0	79
A	23.0	95	57	112	95	0	0
M	30.0	190	60	7	165	25	0
J	37.6	216	29	0	36	179	0
J	35.8	219	80	0	80	139	0
A	31.0	190	132	0	132	58	0
S	31.6	175	23	0	23	152	0
O	23.6	94	102	9	94	0	0
N	13.0	14	86	80	14	0	0
D	9.1	5	70	145	5	0	0
Yearly totals:		1260	952		706	554	246

NOAA model area. Control run data.

Month	T	APE	Prec	St	AE	Def	Surp
J	4.2	3	103	150	3	0	100
F	7.9	10	114	150	10	0	104
M	13.2	34	64	150	34	0	30
A	19.9	81	80	150	81	0	0
M	26.9	162	35	29	156	6	0
J	32.6	205	35	0	64	141	0
J	30.8	199	104	0	104	95	0
A	26.3	150	112	0	112	38	0
S	23.2	105	97	0	97	7	0
O	16.4	50	95	45	50	0	0
N	8.5	12	139	150	12	0	22
D	4.5	3	85	150	3	0	82
Yearly totals:		1013	1063		725	287	338

summer potential evapotranspiration increases from 154 mm to 196 mm in July while the maximum of precipitation shifts to September with 122 mm. Under these altered conditions, only the months from May through September experience more than 50 mm of precipitation. The moist season is shorter and displaced to late summer. With higher potential evapotranspiration and lower precipitation, soil moisture storage is considerably less with the maximum storage of 34 mm occurring in February. The deficit increases markedly to 458 mm annually from the current value of 178 mm, and all months except February and December show some deficit. No month experiences a surplus.

Table 2 provides the same comparison for the NOAA model. While one might expect the water budget based on current data in the area to provide essentially the same results as found for current conditions in Table 1, some differences are found because the actual areas evaluated by the GISS and NOAA models differ. In an area with variable conditions such as those in the Texas-Mexico region, this can lead to differences in average areal temperatures and precipitation. Table 2 (lower portion) shows that current potential evapotranspiration over the NOAA area equals 939 mm compared with 885 mm over the GISS area. Precipitation is somewhat lower, equaling only 613 mm for the NOAA area compared with 707 mm for the GISS area. As a result, soil moisture storage is much lower for current conditions under the NOAA model and the deficit is greater (326 mm vs 178 mm in the GISS model).

Applying the corrections for changes in temperature and precipitation due to a doubling of CO_2 using the NOAA model, annual potential evapotranspiration increases to 1281 mm while precipitation decreases to 560 mm (upper portion). Essentially no water is stored in the soil in the area under the increased CO_2 conditions, the deficit increases to 721 mm and, as before, there is no surplus in any month. The NOAA model postulates very dry conditions for a CO_2 doubling with precipitation some 132 mm less than given in the GISS model and potential evapotranspiration 131 mm greater. Both changes work together to result in much drier soil conditions.

A brief glance at Table 3 reveals one of the significant problems of using the data from the global models directly. The control portion of the table provides the model estimates of current conditions given by the GISS model. Average annual potential evapotranspiration is 752 mm (compared with 885 mm from actual current conditions in Table 1) while average precipitation has increased 1197 mm from 707 mm in Table 1. The GISS model predicts current conditions that are much wetter and somewhat cooler than actually found in the area. All but one month in the year have precipitation values greater than 50 mm; and soil moisture storage is at field capacity (150 mm) in nine of the twelve months, including all summer. Only in the September-November period does soil moisture storage under these modeled conditions drop below field capacity. As a result of the high precipitation and soil moisture conditions, no deficit occurs, while annual surplus equals 445 mm. The GISS control model clearly does not represent current conditions in the area. Since starting conditions are unrealistic, one cannot rely on the absolute value of projections which show a warming of temperature and an increase in potential evapotranspiration from 752 mm to 957 mm. Precipitation decreases slightly from 1197 mm to 1105 mm. As a result, soil moisture storage is slightly drier (only five months with storage at field capacity) and 2 mm of deficit occur in October. Surplus decreases to 150 mm from 445 mm. The estimated conditions for a CO_2 doubling are much more moist than current conditions because the modeled control conditions were initially so moist.

Table 4 shows that the NOAA model also predicts rather wet conditions in the Texas-Mexico area for the control period. Average annual potential evapotranspiration equals 1013 mm while precipitation equals 1063 mm. All but two months have values of precipitation over 50 mm. As a result, soil moisture storage equals field capacity in six months of the year, although it is zero in four months. This rapid change from field capacity to no water in the root zone results in large modeled values for both deficit and surplus (287 mm and 338 mm, respectively) while actual current data reveals a deficit of 178 mm and no surplus.

The NOAA model projects that with a CO_2 doubling, annual potential evapotranspiration equals 1260 mm and precipitation drops to 952 mm. Only three months have soil moisture at field capacity. The deficit increases to 554 mm from 287 mm and the surplus, which still exists, drops from 338 mm to 246 mm. Since the NOAA model predicts rather moist starting conditions as does the GISS model, it provides double CO_2 event conditions that are probably more moist than they should be. The difference between the starting and ending conditions may, however, be indicative of the type of changes resulting from an increase in CO_2. We have, therefore, concentrated on the differences or changes in the water budget factors between either current or control conditions and doubled CO_2 conditions to eliminate some of the errors due to the inability of the models to represent current conditions.

We evaluated water budgets for twelve selected areas (shown in Figure 1) in different climatic regions of the globe, using both the GISS and NOAA models and the two different evaluation techniques described above. The annual values of the water budget factors of prime interest (PE, P, Deficit, Surplus) are summarized in Tables 5 and 6. Table 5 provides information from both the NOAA and GISS models based on the differences between average water budgets evaluated using both current temperatures and percentage changes in precipitation. The results show an increase in potential evapotranspiration in all regions investigated, the NOAA values ranging from just over 100 mm in north central Siberia to just 400 mm in northeast Brazil. The GISS model estimates a larger range of increases, from 75 mm in north central Siberia to nearly 450 mm in northeast Brazil. Agreement is quite reasonable between the two models.

Some investigators have suggested that the increase in CO_2 in the atmosphere will result in greater changes in temperatures in high latitudes than in low latitudes. The picture is one of significant polar warming. While this may be true, it does not necessarily mean that potential evapotranspiration in high latitudes will increase more than in low latitudes. Since potential evapotranspiration is zero until mean monthly temperatures exceed about 0.5°C, increasing air temperatures that are well below freezing will not result in any increase in potential evapotranspiration, while such temperature changes in lower latitudes with temperature well above freezing will result in appreciable changes in potential evapotranspiration. Because of the cold monthly temperatures at high latitudes, increases in temperature due to CO_2 increases may have no significant influence on the potential evapotranspiration in winter. Precipitation generally increases as a résult of the increase

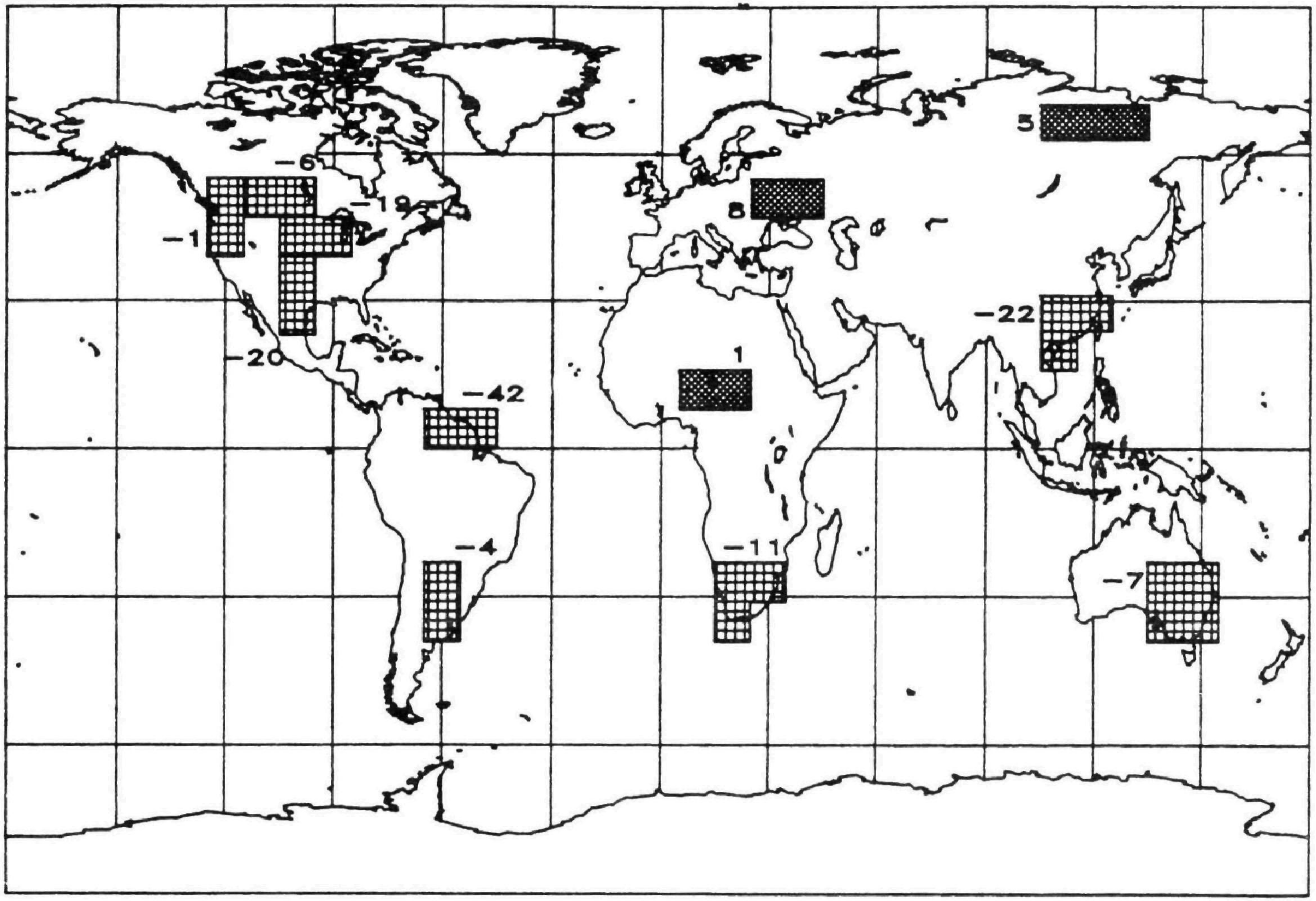


Figure 1. Annual Change in the Moisture Index (I_m)--GISS Model

Table 5. Annual Water Budget Factors for Selected Regions Computed From NOAA and GISS Global Climate Models. (Water budgets computed using current T + ΔT, current P + %ΔP - current T,P).

Location	APE		Prec.		Deficit		Surplus	
	NOAA	GISS	NOAA	GISS	NOAA	GISS	NOAA	GISS
North Central Siberia	119	75	55	70	63	4	0	0
South Central Canada	138	106	208	54	-68	52	2	0
Upper Midwest (USA)	255	149	-8	28	251	75	-13	0
Pacific Northwest	171	122	62	92	142	61	32	32
Ukraine (USSR)	153	97	98	132	85	-26	29	13
Southeast China	143	298	298	103	14	0	168	-195
Texas and North Mexico	342	265	-53	-15	395	280	0	0
West Central Africa	347	426	95	221	253	205	-1	0
Northeast Brazil	380	442	237	-164	155	156	12	-451
Southeast Australia	248	303	-20	53	267	251	0	0
Southern Africa	299	332	-12	66	311	266	0	0
Argentina (Pampas)	191	363	134	291	57	72	0	0

Table 6. Annual Water Budget Factors for Selected Regions Computed From NOAA and GISS Global Climate Models (Water budgets computed using double carbon dioxide T + P - control T + P)

Location	APE		Prec.		Deficit		Surplus	
	NOAA	GISS	NOAA	GISS	NOAA	GISS	NOAA	GISS
North Central Siberia	82	78	131	151	-2	-5	48	68
South Central Canada	146	104	298	114	-42	0	109	10
Upper Midwest (USA)	252	138	-7	60	171	5	-88	-74
Pacific Northwest	151	126	227	236	81	7	157	117
Ukraine (USSR)	174	96	151	164	113	-19	88	49
Southeast China	113	288	19	100	-2	4	-95	-184
Texas and North Mexico	247	205	-111	-92	267	2	-92	-295
West Central Africa	168	528	84	263	84	246	0	-19
Northeast Brazil	198	347	-56	-123	254	471	0	0
Southeast Australia	360	274	-80	110	412	66	-27	-106
Southern Africa	269	277	-11	159	244	1	-36	-117
Argentina (Pampas)	185	291	113	114	78	177	5	0

in CO_2 in the atmosphere. Increases are found in eight of the twelve regions according to the NOAA model and ten of the twelve regions on the basis of the GISS model. Only the Texas-Mexico region shows a precipitation decrease in both models, while the greatest discrepancy occurs in northeastern Brazil where the NOAA model calls for a 237-mm increase in precipitation and the GISS model forecasts a 164-mm decrease in precipitation. The NOAA value must result partly because the model locates the intertropical convergence zone south of the equator under control conditions.

Even though precipitation would generally increase as a result of the greenhouse warming, this additional water is less than the total that would be evaporated by the increased potential evapotranspiration. As a result, the annual deficit would increase in all regions except south central Canada (NOAA) and the Ukraine (GISS). Some of the increases in deficit would be substantial (395 mm in the Texas-Mexico region, 311 mm in South Africa), although the southeast China region shows hardly any increase in deficit at all. Seven of the twelve NOAA regions show either no change in surplus or a decrease, while ten of the twelve GISS regions also show no surplus change or a decrease. Two regions show quite conflicting results in terms of surplus. In southeast China, the NOAA model shows an increase in surplus (because of the great increase in precipitation) while it shows a decrease in surplus with the GISS model. Similarly, northeast Brazil also shows an increase in surplus with the NOAA model and a significant decrease with the GISS model. This difference can be related directly to the modeled values of precipitation which are quite different.

Table 6 is similar to Table 5 except that it presents data obtained from differences in water budget factors determined from modeled control conditions and double CO_2 conditions for both the NOAA and GISS models. Potential evapotranspiration increases in all regions sampled. Precipitation increases in all but five regions using the NOAA model and all but two regions using the GISS model. Deficit increases in all but three regions using the NOAA model and all but two regions with the GISS model. Again a decrease in the deficit is found in south central Canada as in Table 5 in the NOAA model and in the Ukraine in the GISS model. North central Siberia experiences small decreases in deficit according to both the NOAA and GISS models. The surplus decreases or does not change in seven of the twelve regions with the NOAA model and eight of the twelve regions with the GISS model, as might be expected with the increase of potential evapotranspiration. A noticeable increase in dryness occurs in all regions except north central Siberia and south central Canada, the two most poleward regions. The Southern Hemisphere regions sampled exhibit a strong tendency for increased dryness.

The pattern of increased dryness found in most regions on an annual basis is again found if the data for only for the three summer months are considered (Table 7). Decreases in the deficit are found in the Siberian and south central Canada regions according to the GISS and NOAA models, respectively, while a marked decrease in deficit is found in both the NOAA and GISS models in west central Africa. The Ukraine and Argentine Pampas also show a decrease in summer deficit using the NOAA model.

The Thornthwaite-Mather water budget permits the development of a moisture index (I_m), of the relative moisture or dryness of a climate, from a simple comparison of annual precipitation with potential evapotranspiration

Table 7. Summer Water Budget Factors for Selected Regions Computed NOAA and GISS Global Climate Models. (Water budgets computed using current T + ΔT, current P + %ΔP - current T,P).

Location	APE		Prec.		Deficit		Surplus	
	NOAA	GISS	NOAA	GISS	NOAA	GISS	NOAA	GISS
North Central Siberia	38	9	29	35	43	-11	0	0
South Central Canada	20	38	121	23	-61	17	0	0
Upper Midwest (USA)	159	57	-49	7	222	23	0	0
Pacific Northwest	85	45	-7	29	127	27	0	0
Ukraine (USSR)	41	7	23	63	77	-33	0	0
Southeast China	34	109	100	2	0	0	82	-107
Texas and North Mexico	138	128	-19	-10	157	159	0	0
West Central Africa	78	85	104	158	-33	-33	-1	0
Northeast Brazil	116	124	-217	12	0	0	-289	-99
Southeast Australia	105	107	80	38	55	69	0	0
Southern Africa	120	146	7	15	113	130	0	0
Argentina (Pampas)	91	157	111	158	-18	23	0	0

($I_m = 100[(P/PE)-1]$). The data of average annual precipitation and potential evapotranspiration for each of the twelve regions, computed by both the NOAA and GISS models, have been used to determine the moisture index on the basis of both current data and data adjusted for modeled changes in temperature and precipitation. Since the actual value of the moisture index obtained in this way depends on the magnitude of the input data, which varies greatly with the particular circulation model, it was felt that only the difference in the value of the moisture index between current and modeled future conditions should be considered. This would still permit evaluation of whether the climate was becoming relatively more moist or dry and it would allow the results of the two models to be compared even though current input data were quite different. Figures 1 and 2 provide information on the relative change in the moisture index for each of the twelve regions based on the GISS and NOAA models, respectively. In half of the cases, relative changes in the moisture index between current and modeled CO_2 conditions are quite small (ten units or less). In seven of the twelve areas, both models show the same type of change in the moisture index and in all seven of those cases both models indicate a shift to drier conditions. In none of the twelve areas do both indices indicate a shift toward more moist conditions. Areas where one of the models indicates a shift to more moist conditions include north central Siberia, south central Canada, Ukraine, southeastern China, and west central Africa. The shift to drier conditions is most clearly marked in the upper midwest of the United States, the Texas-Mexico area, and northeastern Brazil.

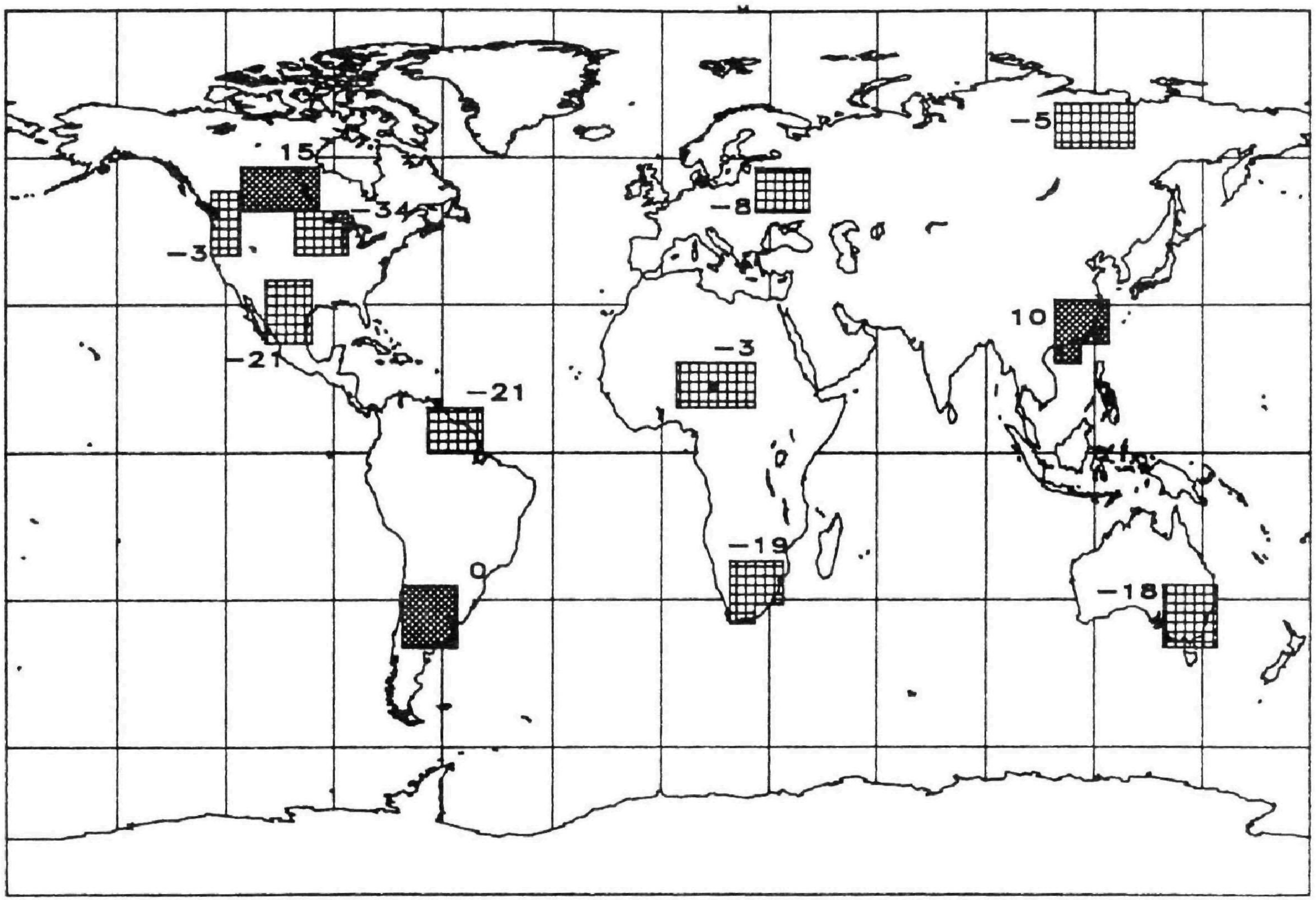


Figure 2. Annual Change in the Moisture Index (I_m)--NOAA Model

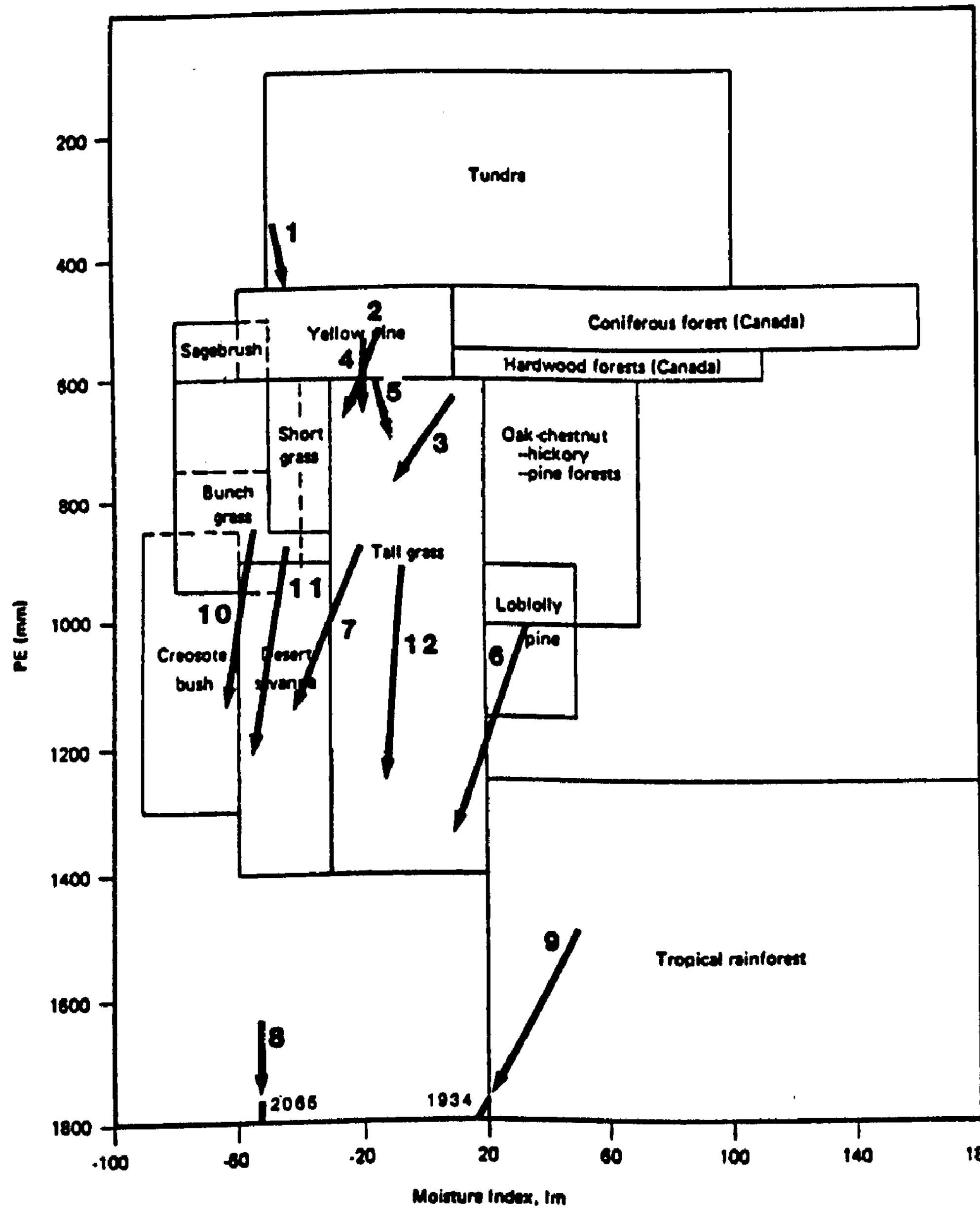
Mather (1978) investigated the relation between the water budget factors of annual potential evapotranspiration and the moisture index, and the distribution of natural vegetation in the United States and Canada. He found that within well-defined ranges of potential evapotranspiration and moisture indices, clearly identified natural vegetation associations exist. Little overlap of vegetation types was found except in the oak-chestnut, hickory, and pine forest regions and in certain dry semiarid vegetation regions. Using the values of annual potential evapotranspiration and moisture index obtained from each of the circulation models under current and modeled CO_2 conditions, it is possible to predict the changes in natural vegetation that might accompany each of the climatic changes that is forecast by the models. Figures 3 and 4 indicate the nature of the vegetation changes for each of the study areas using data from the GISS and NOAA models, respectively. With the NOAA model, five of the twelve areas experience no change in vegetation. In all but two or three cases, the changes that do occur result from both a warming of the climate and a general increase in dryness. Certain change arrows end in regions on the diagram without any vegetation indicated merely because the diagram was constructed for United States and Canadian vegetation (plus tropical rainforest) so that vegetation conditions in other possible ranges of potential evapotranspiration and I_m were not sampled.

CONCLUSION

The present study has had two main goals: to evaluate the effect of increased atmospheric CO_2 on factors of the water budget in twelve selected regions of the world; and to evaluate differences and similarities of two different global models that have been used to provide estimates of future climatic conditions and to consider the results from the different techniques for evaluating the data in order to understand better the problems of trying to estimate future hydrologic conditions.

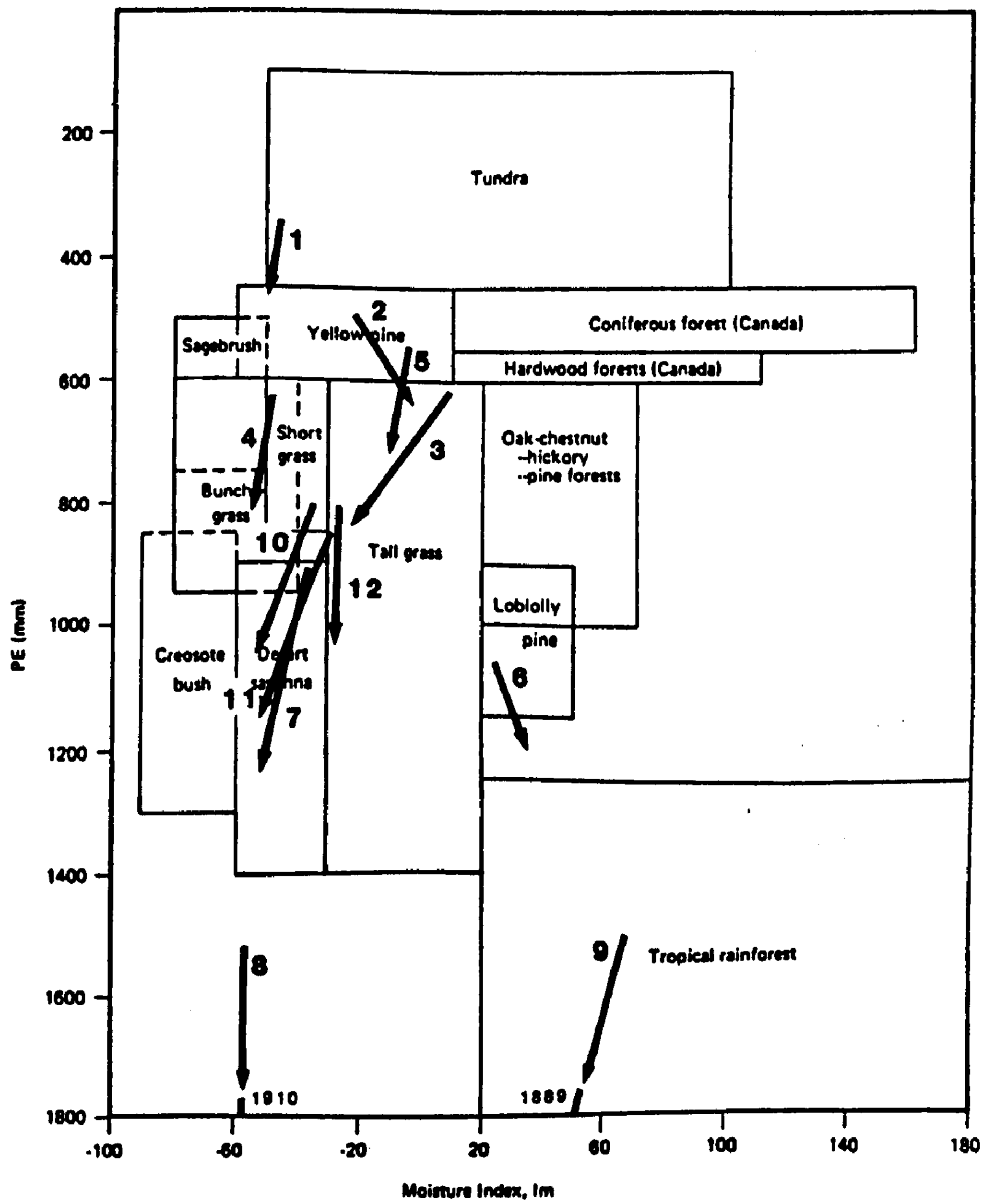
Versions of the NASA/GISS model and the NOAA/GFDL model have been used to provide data of control conditions as well as double CO_2 conditions. Because the control conditions differ significantly from reality, it was felt that the focus of the study should be on differences rather than absolute values of the factors of temperature and precipitation provided by the models. Thus, the two techniques used with each model involved obtaining the differences between double CO_2 conditions and control conditions; and current existing conditions and current conditions as modified by the actual change in temperature and percentage change in precipitation found from the operation of each model.

The results show that the models and analysis techniques do not provide similar estimates of changes in different parts of the world, although there is a general undercurrent of agreement in a majority of the regions. Temperature and hence potential evapotranspiration is predicted to increase in all twelve regions while precipitation is expected to increase in most of the regions. Since the climatic demand for water is expected to increase more than the supply of water by precipitation in most of the regions studied, there is a tendency for most regions to show an increase in annual water deficit, a decrease in annual water surplus, and a decrease in summer soil moisture storage. Both models show exceptions to these conclusions--for example, in the Pacific Northwest (surplus), Ukraine (surplus) and west central Africa (summer soil moisture storage). In a few other cases, one of



1 - North/central Siberia	7 - Texas and N. Mexico
2 - South/central Canada	8 - West/central Africa
3 - Upper midwest (USA)	9 - Northeast Brazil
4 - Pacific northwest	10 - Southeast Australia
5 - Ukraine (USSR)	11 - Southern Africa
6 - Southeast China	12 - Argentina (Pampas)

Figure 3. Predicted Changes in Natural Vegetation in Selected Regions as a Result of Increased Carbon Dioxide--GISS Model



1 - North/central Siberia	7 - Texas and N. Mexico
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Figure 4. Predicted Changes in Natural Vegetation in Selected Regions as a Result of Increased Carbon Dioxide--NOAA Model

the models shows a difference from the foregoing generalizations. The most marked problem areas, where discrepancies are greatest, appeared to be in southeast China and northeast Brazil and probably result from quite different control or current modeled conditions.

Consideration of possible vegetation changes that might accompany the predicted climatic changes calls for changes in natural vegetation in about two-thirds of the twelve regions studied. The changes result in part from the significant warming that will occur in every region and in part from the general increase in dryness in spite of the predicted small increases in precipitation.

The inability of the models to provide a good description of current conditions has been a major drawback to the study. In an effort to deemphasize this problem, differences rather than absolute values were investigated but it is clear that in certain regions where small movements in circulation belts can result in large differences in climatic conditions (e.g., northeast Brazil), even the use of differences may not produce data of great reliability. However, the use of the climatic water budget to evaluate the combined effect of changes in both temperature and precipitation makes it possible to obtain a more rational picture of how increases in CO_2 might affect such hydrologic factors as soil moisture surplus (and hence stream runoff) water deficit and summer soil moisture storage. Because of known relations between water budget factors and natural vegetation, some estimate of how increased CO_2 will modify the distribution of natural vegetation is also possible. The picture is not necessarily bleak but it suggests a general increase in dryness that might lead to changes in vegetation toward a more drought-tolerant type. Marginal areas will be more greatly affected, although some modifications of current moisture relations and hydrologic conditions can be expected nearly everywhere. It is likely that some of our better agricultural areas will experience less favorable conditions in the future. These water budget studies need to be expanded to other areas and the data need to be evaluated at particular points rather than as averages over large geographic areas if we are to understand the real nature of the changes to be expected with increased concentrations of CO_2 and other greenhouse gases.

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HEALTH

The Impact of Human-Induced Climatic Warming Upon Human Mortality: A New York City Case Study

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ABSTRACT

The goal of this study is to determine if weather has an impact on mortality in New York City and to ascertain whether expected future climatic warming will alter the death rates significantly. Summer weather appears to have a significant impact on New York's present mortality rates, and a "threshold temperature" of 92°F was determined, suggesting that mortality increases quite rapidly when the maximum temperature exceeds this value. Days with high minimum temperatures, long periods with temperatures above the threshold, and low relative humidities appear to increase mortality most dramatically. Five climatic scenarios were developed to estimate New York's future weather assuming that warming does occur, and "acclimatized" and "unacclimatized" mortality rates were estimated for each scenario. The unacclimatized rates were computed by using New York's weather/mortality algorithm developed from the historical analysis. Acclimatized rates were computed by selecting present-day "analog cities" which resemble New York's predicted future weather and by developing weather/mortality algorithms for them.

Results indicated that the number of additional deaths at temperatures above the threshold could increase by over tenfold if New Yorkers do not become acclimatized to the warming. The elderly will constitute an increasing proportion of these deaths. However, if full acclimatization occurs, the number of additional deaths above the threshold temperature could be no different than today. No similar relationships were discovered for the winter, and the data suggest that any changes in winter weather will have minimal impact on New York's mortality rates. A preliminary precipitation/mortality study was undertaken, and summer days following a precipitation event had significantly lower mortality rates than summer days without precipitation. In the winter these results were reversed, and days with rain (but no snow) had significantly higher mortality rates than nonprecipitation days.

INTRODUCTION

A procedure has been developed recently to evaluate the impact of long-term climatic warming on inter-regional variations in human mortality. Fifteen cities around the country are presently being evaluated, possible future climatic scenarios are being developed for each, and estimates of possible weather-related changes in mortality are being calculated.

The objective of this report is to describe our procedure and to apply it to one of our fifteen cities, i.e., New York City, New York. The impact of present-day weather on New York's present mortality rates is discussed, and estimates are presented describing the potential impact of climatic warming on New York's future mortality.

Although no previous study has attempted to predict the impact of future weather changes on mortality, there has been considerable work relating to present climate/mortality relationships. For example, studies at the Centers for Disease Control have identified a number of factors that may accelerate the onset of heat stroke, including decreases in use of air conditioning, consumption of fluids, and living in well-shaded residences (Kilbourne et al. 1982). However, other researchers have found that many causes of deaths other than heat stroke increase during extreme weather (Applegate et al. 1981; Jones et al. 1982). In addition, it has been shown that mortality attributed to weather varies considerably with age, sex, and race, although there is disagreement among researchers in defining the most susceptible population group (Oechsli and Buechley 1970; Bridger, Ellis, and Taylor 1976; Lye and Kamal 1977; Jones et al. 1982). The impact of cold weather is less dramatic than hot weather, although mortality increases have been noted during extreme cold waves (Centers for Disease Control 1982; Fitzgerald and Jessop 1982; Gallow, Graham, and Pfeiffer 1984).

This study will incorporate some approaches used in previous studies while offering a new approach to account for potential changes in mortality/weather relationships that might be attributed to acclimatization.

PROCEDURE

A very detailed mortality data base is presently available from the National Center for Health Statistics (NCHS), which contains records for every person who has died in this country from 1964-present (National Center for Health Statistics 1978). The data contain information such as cause of death, place of death, age of death, date of death, sex, and race. These data were extracted for the New York Standard Metropolitan Statistical Area for 11 years: 1964-66, 1972-78, and 1980 (during intervening years, a sizable amount of information was missing from many records). The number of deaths for each day were tabulated and divided into categories of total deaths and elderly deaths (65 years and older). These daily death totals were standardized to conform to a hypothetical "standardized city," which contains fixed population characteristics (Table 1). The death rates for New York were adapted to the population characteristics of the standardized city to conform to procedures commonly found in the epidemiological literature (Mausner and Bahn 1974; Lilienfeld 1980). The advantages of this standardization procedure are twofold. First, when the study is extended beyond New York, inter-city

Table 1. Population Characteristics of the Standardized City

Total Population	3,811,000
Male	1,833,000
Female	1,978,000
White	2,817,000
Non-White	993,000
Age Groups	
0-4 Years	263,000
5-17 Years	759,000
18-24 Years	493,000
25-44 Years	1,122,000
45-64 Years	764,000
65 Years	411,000

comparisons will be feasible since demography is kept constant. Second, if a city has grown rapidly during the study period, the bias introduced by the increase in deaths that are due to population growth is eliminated, and changes in mortality attributed to environmental factors can be better assessed.

Apparently weather does have some impact on daily mortality (Figure 1). During the heat wave of late July 1980 in New York, standardized deaths rose by over 50% above normal on the day with the highest maximum temperature. Elderly deaths showed similar increases. In this study, daily changes in mortality were compared to nine different weather elements that might have some influence on death rates (Table 2).

Initial observations of daily standardized deaths vs. maximum temperature suggest that weather has an impact only on the warmest 10%-20% of the days; however, the relationship on those very warm days is impressive (see Figure 2). Figures similar to Figure 2 were developed to compare the maximum temperature on the day of the deaths, as well as one, two, and three days prior to the day of deaths to determine if a time-lag exists between weather and the mortality response. In the case of New York, there is a one-day lag between weather and mortality. In addition, a "threshold temperature," which is the maximum temperature above which mortality increases, can be determined. The threshold temperature can be calculated objectively by using a sum of squares technique (Kalkstein 1986). The threshold temperature for total deaths in New York was 92°F; mortality increased dramatically at temperatures above this level. This procedure can be repeated for winter, where the threshold temperature represents the temperature below which mortality increases.

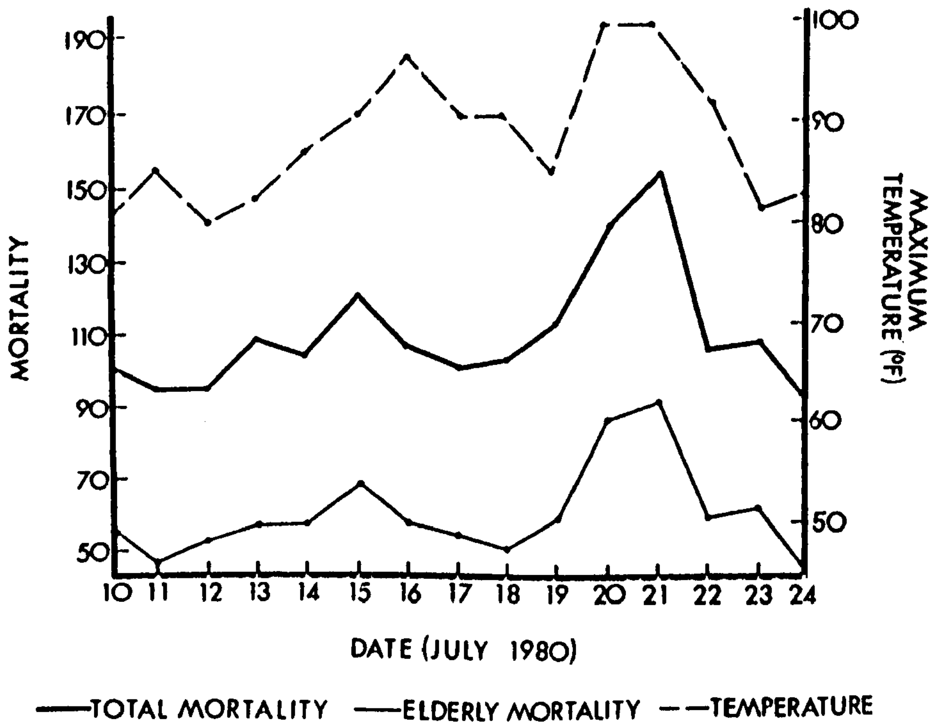

Figure 1. Mortality During a 1980 Heat Wave in New York City

Table 2. Weather Variables Used in the Mortality Study

Maximum Temperature
Minimum Temperature
Maximum Dewpoint
Minimum Dewpoint
Heating Degree Hours (HDH)*
3AM Visibility
3PM Visibility
3AM Wind Speed
3PM Wind Speed

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* HDH is calculated by determining the total number of degrees that the temperature is above 90° for the day. If the temperature exceeds 90° for 2 hours on a given day, HDH is calculated as the sum of the degrees above 90 for those 2 hours.

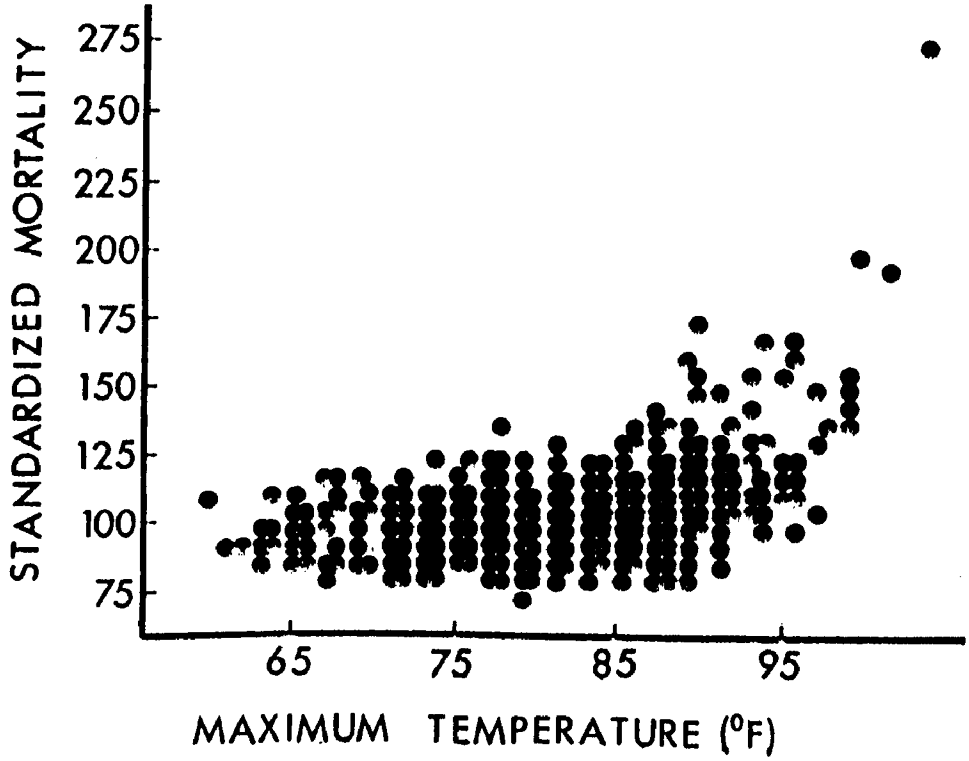

Figure 2. Daily Summer-Season Standardized Mortality vs. Maximum Temperature: New York One Day Lag

Once the threshold was established, a multiple regression analysis was performed using the weather elements described previously to determine the weather/mortality relationship for days above the threshold temperature. When a statistically meaningful relationship was determined, an algorithm was developed and used to predict the expected increases in mortality at temperatures above the threshold.

The next step was an attempt to estimate changes in New York's mortality that might occur with the predicted climatic warming. In consultation with EPA and the NASA-Goddard Institute for Space Sciences, investigators developed future weather scenarios for New York by adding temperature increments to existing historical New York temperatures. These scenarios were created for the period recorded by adding 1°, 2°, 4°, 5°, and 7°F to the existing weather data. This produced an approximation of what New York's temperature regime could be over the next 100 years. New mortality estimates were created for each of the temperature increments by using the algorithm developed from the historical data evaluation.

When measuring the impact of warming on future mortality, the question of acclimatization had to considered. Will New Yorkers react to heat as they do today, or will their reaction be similar to people who presently live in hotter climates? There is much disagreement in the literature concerning human acclimatization to changing weather. Some research indicates that acclimatization responses are very rapid (Rotton 1983); others think that it is a much slower process (Ellis 1972; Kalkstein and Davis 1985), and a few suggest that virtually no acclimatization occurs at all (Steadman, 1979). It is obvious that the full range of possibilities must be examined in this study. First, the historical algorithm that was developed from the previously described multiple regression procedure was applied to the future weather scenarios with the incorporated incremental increases in temperature. The mortality increases estimated from this procedure imply no acclimatization because an assumption is made that New Yorkers will respond to heat in the future in much the same way that they do today. Second, analog cities for New York were established to account for full acclimatization. For example, by adding the temperature increment to New York's present temperature regime, its weather will approximate another city's present weather in the U.S. A 5°F increment added to New York's present summer temperatures will yield a regime approximating that of Norfolk, Virginia, today. Since Norfolk residents are fully acclimatized to this regime, the weather/mortality algorithm developed for Norfolk can be utilized for New York to account for full acclimatization when New York's temperatures rise by 5°F.

Present-day analogs to account for full acclimatization were selected for New York for the 1°, 2°, 4°, 5°, and 7°F increments, and mortality models similar to the one described for New York were created for them. The analog cities were determined by computing for the three summer months (June, July, August) mean maximum temperatures, mean minimum temperatures, and mean number of days with maximum temperatures over 90°F for over 100 cities in the United States. The city that best duplicated New York's regime was established as an analogue city. This was achieved objectively using a variety of statistics for model evaluation (Willmott et al. 1985).

Figure 3 illustrates the hypothetical differences expected in mortality with full and no acclimatization. It is probable that the warmer analogs will show smaller increases in mortality than the original New York model since residents are already acclimatized to the increased warmth. Thus, for warming scenarios of 7° or more, the differences in predicted deaths between full and no acclimatization situations may be very large (area hatched between lines 1 and 2). In certain cases, it is possible that no extra deaths will be predicated for full acclimatization, as residents will be conditioned to hot weather. For example, in Jacksonville, Florida, heat waves appear to produce no extra deaths (see Figure 4). The relationship is so poor that it is almost impossible to determine a threshold temperature.

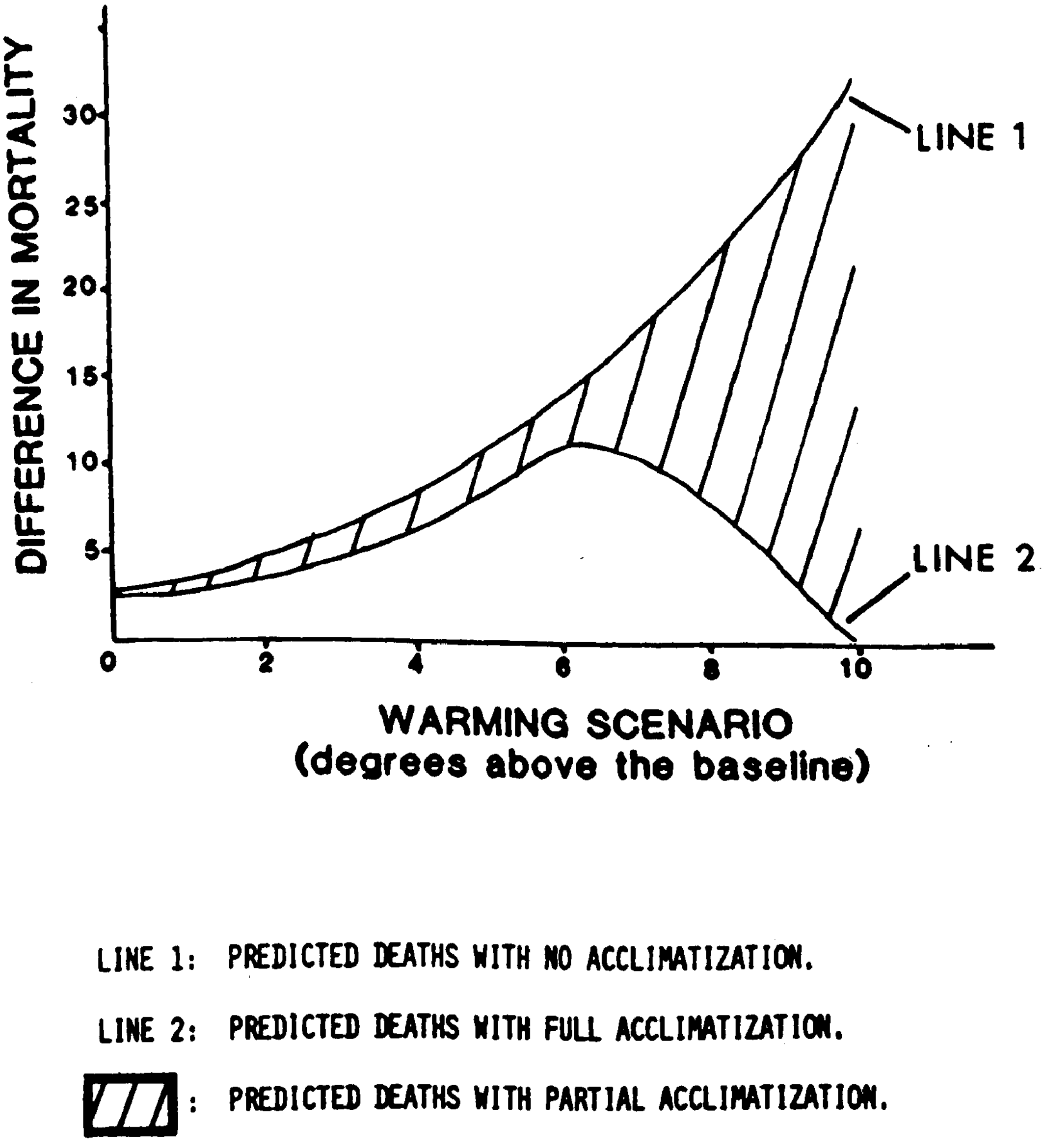

Figure 3. Expected Increases in Mortality in the Target City for Different Warming Scenarios

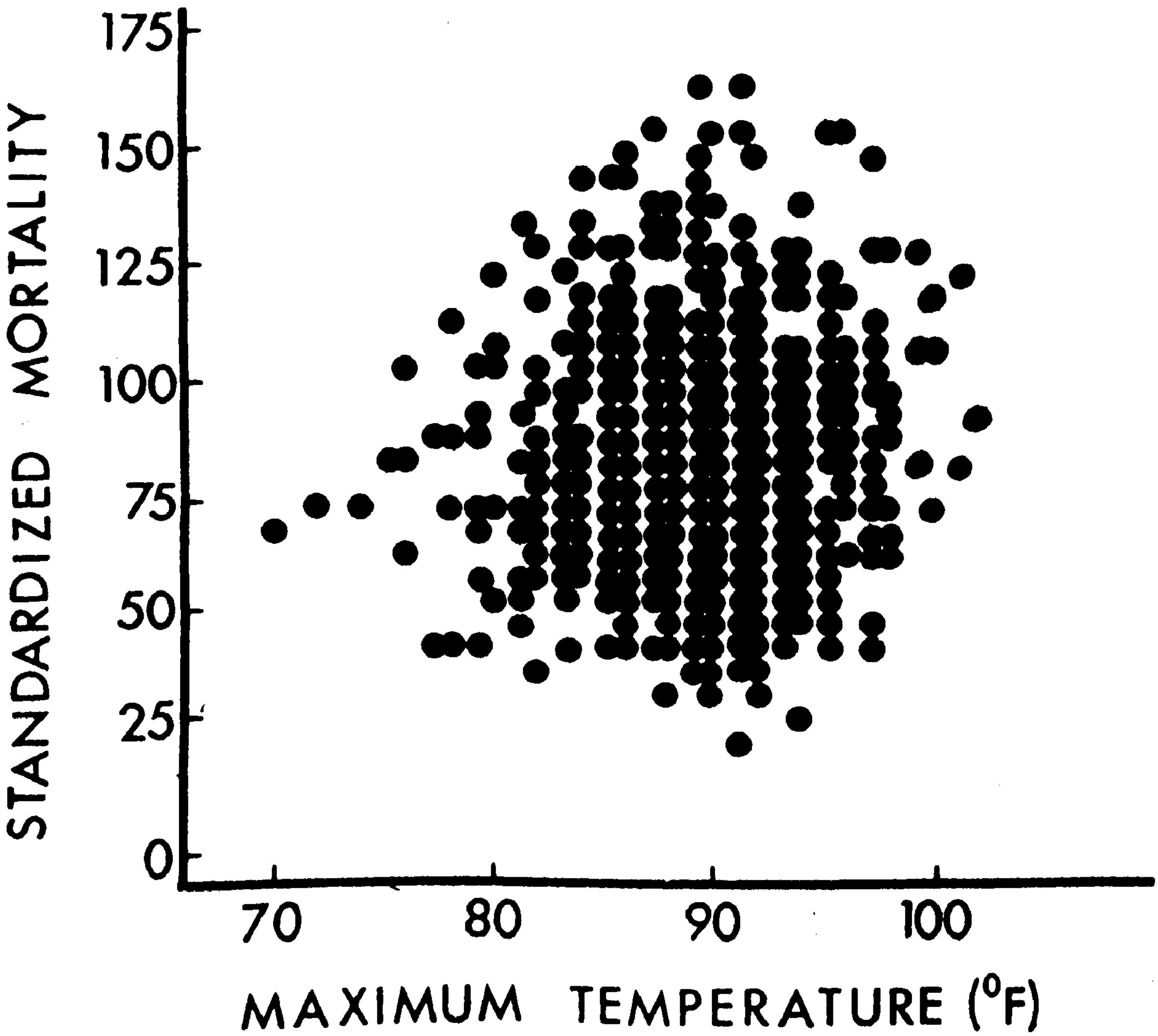

Figure 4. Daily Summer-Season Standardized Mortality vs. Maximum Temperature: Jacksonville One Day Lag

RESULTS

The multiple regression analysis to determine those weather elements having the greatest impact on present-day mortality in New York produced a surprisingly strong relationship (Table 3). Minimum temperature, maximum dewpoint, and heating degree hours (HDH) were all highly statistically significant and explained almost 66% of the variance in mortality at temperatures above the threshold. The most offending days appeared to possess high minimum temperatures, high HDH values, and low dewpoints, indicating that hot, dry conditions in New York appear most conducive to rises in mortality. The results from the evaluation of the elderly were similar, and the explained variance was slightly higher. Thus, it appears that predictive algorithms can be developed to estimate mortality in New York at temperatures above the threshold. These algorithms were also used to estimate unacclimatized deaths in New York using each of the warming scenarios.

Next, the analog cities were determined, threshold temperatures were calculated, and multiple regressions were developed for each (Table 4). As expected, the relationships became progressively worse for the analog cities representing the warmest scenarios, and the lack of a weather/mortality relationship for Norfolk and Jacksonville indicated that people in those cities were not sensitive to even the warmest temperatures because they are fully acclimatized to the frequent heat. Thus, there would be no expected increase in mortality in New York for the 5° and 7°F scenarios if the people become fully acclimatized. Note that threshold temperatures were higher for the warmer analog cities, supporting the contention that the impact of weather on mortality is relative on an inter-regional scale.

The number of deaths predicted from the nonacclimatized New York algorithm increased very rapidly with each succeeding warming scenario. One of the reasons for this was the increasing number of days exceeding New York's threshold temperature of 92°F for the warmer scenarios (Table 5). At present, the average monthly percentage of days exceeding this threshold is 3.3% in June, 10% in July, and 3.6% in August. Thus, for an average summer season, only 5.7% of the total days exceed the threshold temperature. These percentages increase steadily as the predicted warming increases, and for the 7°F scenario, almost half of the days in July and over one-third of the days in the entire summer season exceed the threshold. Obviously the total number of days with heat-related increases in mortality will also increase if there is no acclimatization.

A comparison of expected mortality increases for all age groups with no and with full acclimatization showed dramatic differences (Table 6). At present in New York, the average number of additional standardized deaths that occur on days above the threshold temperature each month is 19 in June, 86 in July, and 25 in August (the raw, unstandardized totals for New York are considerably higher, but these figures should be used with caution). Using the algorithm for no acclimatization, these figures more than doubled with a 2°F rise in temperature, and increased by more than tenfold with a 7°F rise. Thus, if New Yorkers do not acclimatize to the increasing warmth, it is predicted that the average number of additional standardized deaths will exceed 1300 each summer season if the weather warms by 7°F (the raw totals will exceed 3200). The full acclimatization results showed much different

Table 3. Results of the Regression Analysis for Mortality Climate Relationships

Variable	Coef.	R^2	R^2 Improv.	Level of Signif.
Total Deaths				
Minimum Temp. (MT)	+2.60	.306	.306	.005
Heating Degree Hrs. (HDH)	+0.66	.593	.287	.005
Maximum Dewpoint (MD)	-1.48	.659	.066	.010
Intercept	+12.01			
Total Death Algorithm: Y = 12.01 + 2.60 (MT) + 0.66 (HDH) - 1.48 (MD)				
Elderly Deaths				
Heating Degree Hrs. (HDH)	+0.51	.298	.298	.001
Minimum Temp. (MT)	+1.98	.567	.269	.001
Maximum Dewpoint (MD)	-1.55	.668	.101	.010
Intercept	+20.76			
Elderly Death Algorithm: Y = 20.76 + 0.51 (HDH) + 1.98 (MT) - 1.55 (MD)				

Table 4. New York's Analog Cities, Their Threshold Temperatures, and the R^2 of Their Regression Models

Warming Scenario	Analog City	Total/ Elderly	Threshold Temp.	% of Days Above Threshold	R^2 of Reg. Model
1°F	Indianapolis	total	91°F	10.9	.092
		elderly	91°F	10.9	.078
2°F	Philadelphia	total	91°F	13.5	.210
		elderly	91°F	13.5	.240
4°F	Atlanta	total	94°F	4.6	.200
		elderly	92°F	7.8	.200
5°F	Norfolk	total	94°F	7.5	non-
		elderly	94°F	7.5	significant
7°F	Jacksonville	total	96°F	10.5	non-
		elderly	96°F	10.5	significant

Table 5. Percentage of Days Above the Threshold Temperature for the Six Warming Scenarios for New York

	Degrees Above Present					
Month	0	1	2	4	5	7
June	3.3%	7.0%	8.5%	12.1%	15.2%	19.7%
July	10.0%	12.3%	16.7%	25.8%	31.7%	46.0%
August	3.6%	5.5%	8.8%	21.5%	26.4%	40.0%
Season	5.7%	8.3%	11.4%	19.9%	24.5%	35.4%

Table 6. Average Monthly Increase in Total Mortality for the Various Warming Scenarios in New York[a,b]

NO ACCLIMATIZATION

Month	Degrees Above Present 0	1	2	4	5	7
June	19(45)	34(81)	57(138)	5(12)	156(373)	253(605)
July	86(206)	110(263)	154(368)	282(674)	372(890)	622(1488)
August	25(60)	37(88)	64(153)	170(407)	250(598)	487(1165)
Total	130(311)	181(432)	276(657)	56(1354)	778(1861)	1362(3258)

FULL ACCLIMATIZATION

Month	Degrees Above Present 0	1	2	4	5	7
June	19(45)	33(79)	32(77)	5(12)	0	0
July	86(206)	62(148)	54(129)	11(26)	0	0
August	25(60)	29(69)	55(132)	4(10)	0	0
Total	130(311)	124(296)	141(338)	20(48)	0	0

[a] Numbers in parentheses represent raw, unstandardized mortality estimates. They are calculated by multiplying the standardized values by 2.39. The population of the New York metropolitan area in 2980 was 9,120,000, which is 2.39 times the population of the standardized city (3,811,000).

[b] These values are not adjusted for potential future population increases.

trends. The seasonal number of standardized deaths remained virtually constant with a 1°F rise (this was calculated using the present-day Indianapolis algorithm, which represents New York's analog city for a 1°F rise), and rose only slightly with a 2°F increase (Philadelphia's algorithm). However, for the warmer scenarios, the acclimatized deaths dropped sharply, and no additional deaths were predicted at 5° and 7°F warming. These results reflect the present-day Norfolk and Jacksonville situation, where no additional deaths are noted at temperatures exceeding the threshold.

The actual number of deaths attributed to future warming will fall somewhere between the predicted values for nonacclimatization and full acclimatization, but the precise impact of future acclimatization is obviously unknown. We suggest that a lag in acclimatization to climatic change is likely, and factors such as the physical composition of the city (i.e., building construction designed to accommodate present weather conditions) will delay or prevent full acclimatization. Thus, it is improbable that New Yorkers will become as totally insensitive to hot weather as Jacksonville residents are today, and the decrease in weather-related mortality predicted by the full acclimatization model is highly unlikely.

Predicted mortality increases for the elderly show similar trends (Table 7). Very large increases are noted with no acclimatization (raw unstandardized values are not provided, as they are partially dependent upon demographic information which is unknown, such as the proportion of population in the elderly category when a 7°F rise is achieved). However, deaths once again decrease to zero with full acclimatization. There is some indication that the elderly will constitute an increasing proportion of the total mortality as the climate warms (Table 8). At present, the percentage of the standardized mortality that is attributed to the elderly at temperatures above the threshold is 64% in June, 70% in July, and 54% in August. Using the algorithms for no acclimatization, this proportion is predicted to rise significantly as the weather warms, and since the deaths are standardized, this does not assume that the elderly will constitute a larger proportion of the population in the future.

An attempt was made to duplicate the procedure to determine the impact of winter weather on mortality using the same warming scenarios. Winter analog cities were selected, threshold temperatures were determined, and multiple regressions were performed, but the relationships for New York and the analog cities were unimpressive for winter (Table 9). Since their explained variance was low, the models were not robust enough to produce any predictive algorithms. Although findings will probably differ for other evaluated cities, these results suggest that any change in winter weather in the future will have little impact on weather-related mortality in New York.

A final aspect in the New York analysis was an attempt to determine if precipitation has any effect upon mortality. No attempt to estimate future impacts of precipitation was made, and the study concentrated on historical relationships only. It appears that precipitation may have an impact on mortality during both summer and winter (Table 10); however, unlike the temperature relationships, its influence does not appear to increase steadily as precipitation amounts increase. Thus, the precipitation evaluation was

Table 7. Average Monthly Increase in Elderly Mortality for the Various Warming Scenarios in New York

NO ACCLIMATIZATION

Month	0	1	2	4	5	7
	Degrees Above Present					
June	12	23	41	88	116	192
July	60	81	107	199	266	447
August	13	21	36	104	161	321
Total	85	125	184	391	521	960

NO ACCLIMATIZATION

Month	0	1	2	4	5	7
	Degrees Above Present					
June	12	19	25	11	0	0
July	60	47	42	22	0	0
August	13	24	38	12	0	0
Total	85	91	105	45	0	0

Table 8. Percent of Total Mortality Increase Attributed to the Elderly for the Six Warming Scenarios

	Degrees Above Present					
Month	0	1	2	4	5	7
June	64%	67%	72%	77%	74%	76%
July	70%	74%	70%	70%	72%	72%
August	54%	57%	55%	61%	64%	66%

Table 9. Winter Relationships Between Weather and Mortality for New York and Two of Its Analogs

City	Total/ Elderly	Lag Time With Best Fit	R^2 of Regression Model
New York	total	0	.069
	elderly	0	.142
Nashville (5° Analog)	total	0	.132
	elderly	0	.079
Norfolk (7° Analog)	total	1	.064
	elderly	1	.082

Table 10. Relationships Between Precipitation and Mortality in New York[a]

Variables	Mean Mortality for Each Variable[b]	N for Each Variable[c]	T-Statistic[d]	Significant Level
Summer				
Precipitation vs. No Precipitation	-0.135 0.100	310 425	3.235	0.001
Winter				
Precipitation vs. No Precipitation	0.087 -0.079	342 378	2.241	0.025
Rain vs. No Precipitation	0.192 -0.079	119 378		
Snowfall vs. No Precipitation	0.045 -0.079	140 378	1.324	0.187[e]
3" Snow on Ground vs. No Snow on Ground	0.336 -0.038	47 392	2.489	0.013

[a] All best-fit relationships possessed a one-day lag between the precipitation event and the mortality response.
[b] Expressed as standard deviations from the overall daily mean.
[c] Number of days in the sample.
[d] T-statistic comparing the means of two samples, assuming that variances are not equal.
[e] Not statistically significant.

limited to comparing mortality rates during periods of precipitation and nonprecipitation and determining if the difference in the mean daily mortality rates was statistically significant between the two periods. It appears that a one-day lag exists between the precipitation episode and the mortality response during all seasons, and that the strongest correlation between these variables occurred in summer. On summer days with precipitation, mortality averaged .135 standard deviation below the mean, but on those days without precipitation, mortality averaged .100 standard deviation above the mean. One possible explanation for this relationship is that summer rain may provide a refreshing, cooling influence which tends to lessen discomfort and therefore, to lower mortality. Some strong winter relationships were also discovered, and rain appeared to have a greater influence on mortality than snowfall. A significant relationship was determined between all precipitation and no precipitation days, but when precipitation was subdivided into rain and snowfall, only the rain relationship proved to be statistically significant. Unlike the summer findings, mortality was significantly higher on days with rainfall, and mean daily mortality rate was almost .200 standard deviation above the mean on those days. Although days with snow falling appeared to have little impact on mortality, days with significant accumulations on the ground did correspond with higher mortality rates. Those days with three or more inches of snow on the ground averaged over .330 standard deviation above the mean.

CONCLUSION

The objectives of this study were to determine the historical relationships between weather and mortality and to estimate the possible impact of long-term climatic warming on future mortality rates in New York City. During the summer, weather appears to exert a significant influence on mortality in New York, but the future impact is largely dependent on whether New Yorkers will acclimatize to the predicted increasing warmth. If acclimatization is slow or is nonexistent, thousands of additional deaths may occur during each summer season if the mean temperature warms to 7°F above present levels. However, changes in winter weather should have little impact on mortality.

This study will be expanded to include fourteen additional cities around the United States. Analog cities will be determined, and inter-regional influences of weather will be examined. In addition, mortality rates will be subdivided by race and additional age categories, and those causes of death that are considered to be weather-related will be isolated and independently evaluated.

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