POTENTIAL EFFECTS OF FUTURE CLIMATE CHANGES ON FORESTS AND VEGETATION, AGRICULTURE, WATER RESOURCES, AND HUMAN HEALTH

APPENDIX B

Edited by

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October 1986

* * * DRAFT FINAL * * *

PREFACE

This report was prepared as part of the United States Environmental Protection Agency's review of information on Stratospheric Ozone Modification. The review was conducted in conjunction with the United Nations Environment Programme as partial fulfillment of requirements of the Vienna Convention on the Protection of the Ozone Layer. It is a summary, integration, and interpretation of the current scientific understanding of the effects of potential global climate change in the areas of forest and vegetation, agriculture, water resources, and human health.

This appendix is a multi-authored review of the scientific literature on the effects of global climate change. Direct effects of CO_2 are generally not included because they have been recently reviewed elsewhere. The authors have attempted to consciously write for the informed lay person and to draw together interpretive evidence from the literature. The document was not designed to set standards or to suggest regulatory policies or recommendations. It was designed to provide supplementary information for use by the Environmental Protection Agency (EPA) as it assesses the impact of chemicals on the stratospheric ozone layer.

ACKNOWLEDGEMENTS

The editor is indebted to the members of the EPA staff and the scientific community who have reviewed this document and provided many suggestions to improve its contents. In particular, Holly Stallworth, David Bennett, and Susan Farris are to be acknowledged for their editorial assistance. Finally, this report could not have been written without the dedicated and constructive contributions of each of the authors.

This draft will be revised after review by EPA's Scientific Advisory Committee and other scientists. The final version of this report will be published as part of the agency's Stratospheric Ozone Assessment Review Document.

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I. SUMMARY

The greenhouse effect resulting from increased levels of CO_2, chloroflurocarbons, methane, N_2O, and other trace gases in the atmosphere has been recognized by the scientific community for several decades as a potential cause of future climate change. In the last few years, estimates of the rate of change of these gases in the atmosphere has heightened concern about global warming and associated climate and environmental change. Chapter 6--Global Warming--presents a review of recent chemical and physical evidence supporting the greenhouse phenomenon. From this evidence it is generally concluded that in the relatively short period of time of the next 50-100 years the earth's climate will undergo important changes. These include: potential increases in temperatures, changes in precipitation, humidity, windfields, ocean currents, and the frequency of extreme events such as hurricanes. Furthermore, these climate parameters will induce still other shifts in sea levels, ice margins, the hydrologic cycle, air pollution episodes and other phenomenon.

Recently the World Meterological Organization (WMO), the United Nations Environment Programme (UNEP) and the International Council of Scientific Union (ICSU) summarized current scientific data on global climate change. These findings are presented in Exhibit 1-1. Similar findings have been reported by NAS (1979 and 1982).

EXHIBIT 1-1

Summary of Findings from the WMO/UNEP/ICSU Conference on Global Climate Held in Villach, Austria, October 1985

- Many important economic and social decisions are being made today on long-term projects -- major water resource management activities such as irrigation and hydro-power, drought relief, agricultural land use, structural designs and coastal engineering projects, and energy planning -- all based on the assumption that past climatic data, without modification, are a reliable guide to the future climate conditions. This is no longer a valid assumption, since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of future climate conditions to improve these decisions.

- The amounts of some trace gases in the troposhere, notably carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), ozone (O_3), and chlorofluorocarbons (CFCs), are increasing. These gases are essentially transparent to incoming short-wave solar radiation, but absorb and emit long-wave radiation and are thus able to influence the earth's climate.

- The role of greenhouse gases other than CO_2 in changing the climate is already about as important as that of CO_2. If present trends continue, the combined concentrations of atmospheric CO_2 and other greenhouse gases would be (radiatively) equivalent to a doubling of CO_2 from pre-industrial levels, possibly as early as the 2030's.

- The most advanced experiments with general circulation models of the climatic system show increases of the global mean equilibrium surface temperature of between 1.5°C and 4.5°C for a doubling of the atmospheric CO_2 concentration or equivalent. Because of the complexity of the climatic system and the imperfections of the models, particularly with respect to ocean-atmosphere interactions and clouds, values outside of this range cannot be excluded. The realization of such changes will be slowed by the inertia of the oceans; the delay in reaching the mean equilibrium temperatures corresponding to doubled greenhouse gas concentrations is expected to be a matter of decades.

- While other factors such as aerosol concentrations, changes in solar energy input, and changes in vegetation may also influence climate, the increased amounts of greenhouse gases are likely to be the most important cause of climate change over the next century.

- Regional scale changes in climate have not yet been modelled with confidence. However, regional differences from the global averages show that warming may be greater in high latitudes during late autumn and winter than in the tropics; annual mean runoff may increase in high latitudes; and summer dryness may become more frequent over the continents at middle latitude in the Northern Hemisphere. In tropical regions, temperature increases are expected to be smaller than the average global rise, but the effects on ecosystems and humans could have far-reaching consequences. Potential evapotranspiration probably will increase throughout the tropics, whereas in moist, tropical regions, convective rainfall could increase.

- Based on the observed changes since the beginning of this century, it is estimated that global warming of 1.5°C to 4.5°C would lead to a sea-level rise of 20 to 140 cm. A sea-level rise in the upper portion of this range would have major direct effects on coastal areas and estuaries. A significant melting of the West Antarctic ice sheet leading to a much larger rise in sea level, although possible at some future date, is not expected during the next century.

- Based on analyses of observational data, the estimated increase in global mean temperature of between 0.3°C and 0.7°C during the last 100 years is consistent with the projected temperature increase attributable to the observed increase in CO_2 and other greenhouse gases, although it cannot be ascribed in a scientifically vigorous manner to these factors alone.

- Based on evidence of the effects of past climate changes, there is little doubt that a future change in climate of the magnitude obtained from climate models could have a profound effect on global ecosystems, agriculture, water resources, and sea ice.

As noted in the WMO/UNEP/ICSU report the projected changes in climate will have important impacts on all aspects of society. Agriculture, forests, human health, water resources, energy planning, and recreation are among the sectors likely to be affected. Moreover, all these sectors are likely to be affected simultaneously throughout the world, but to different extents. Today we know a great deal from paleoclimatic records about how past shifts in climate affected the growth and development of forest systems, the location of lakes, and development of agriculture. But the changes that occurred to these systems in the past took 18 to 20 thousand years to unfold as the earth warmed approximately 4°C-5°C. During that time, forest composition shifted, some lake systems were lost and new ones were formed. Most importantly, the changes took place during a period when the earth's population was small and civilizations were in formative stages.

Today modern society is much more complex, but still vulnerable to climatic changes. Our industrial society relies on a sustained climate to replenish natural resources as a source of raw materials, for transport of goods, and for the food we eat. We assume that the climate that supports our society, while variable and difficult to predict over short periods, will not shift appreciably. Indeed, most decisions made by farmers, forest managers, state and local water management officials, utility executives, and government policy makers assume that climate will be constant. However, if current predictions from global climate models prove to be correct, some increase in global temperatures may be inevitable simply because of the presence of trace gases which have already been emitted to the atmosphere.

Our current understanding of the effects of global climate change on the environment is incomplete. Moreover, several features of the greenhouse phenomenon make it unique, different from other environmental issues, and difficult to analyze. Among these features are the following:

- The effects will not take place immediately, but over several decades.

- The effects will be virtually irreversible over several centuries.

- All nations of the world will experience the effects at the same time.

- There is no historical analog for the amount of global warming likely to occur in the relatively short period of the next 50 to 100 years.

Scientists have only begun to analyze the potential impacts from global warming and changes in other climate variables. Insights are available from historical data and from the application of predictive models. In most cases, however, our understanding of the consequences, both beneficial and detrimental, is in a formative stage. Historical analogs provide qualitative information about likely effects, but they cannot predict the future because the anticipated increase in temperature and the rate of that increase are beyond the range of previous warm periods. Prediction models of both the climate system and potential effects often do not include complete parameterizations of important system variables. Thus, more advanced global climate models capable of providing regional predictions are needed, and more comprehensive and sophisticated analyses of environmental effects are necessary to understand fully the implications throughout the world. Recognizing these limitations, the following section summarizes what is known about climate impacts on the environment with emphasis on forests, agriculture, water resources, and human health. Perhaps of equal importance are potential impacts which have not been reported or analyzed, including potential impacts on national parks, ports, electricity demand and supply, population shifts, work-place absentee rates, hurricane frequency, air pollution emissions, wildlife management, and our national security. These potential impact areas and many others represent the challenges to be investigated as the science supporting predictions of global climate change improves.

The greenhouse phenomenon challenges the scientific community in an unprecedented manner. In almost all areas, substantial additional research remains to be done before the effects of climate change can be predicted with certainty. However, the body of literature on future climate effects is growing, and this summary attempts to provide an accurate and impartial evaluation of what is known about these effects. The following are general findings that are common to several areas reviewed in this report. Other more detailed findings are to be found at the beginning of each section.

1. <u>Paleoecological and paleoclimatological records indicate that, for a global warming which is nearly the equivalent of the predicted future temperature of 1.5°-4.5°C, substantial changes have occurred to forest, agriculture, and water resource systems throughout the globe</u>.

2. <u>Available paleoclimatic data do not provide an analog for the high rate of climate change that is predicted to occur over the next 50 to 100 years</u>. Previous

environmental changes, since the last ice age, took thousands of years to evolve rather than the predicted decadal changes.

3. Limited analyses and experiments with models of forest, agriculture, and water resource systems suggest that major changes are likely to occur over the next 50-100 years as a result of global warming. For example, current analyses suggest an intensified hydrologic cycle will accompany predicted global warming.

4. Even relatively small changes in global temperatures could affect agriculture and forest systems in regions that are near the maximum tolerance limits for sensitive species.

5. Accommodating to small changes in climate may be possible, but the costs, which are not currently estimated, are likely to be large. For example, agriculture may need to shift to new lands and crops, to improve or develop new irrigation systems, to develop improved soil management and pest control programs, and to design heat/drought-tolerant species. Forest managers may need to adjust forest technology, planning, and tree breeding programs. Many large-scale water management projects may need to be analyzed with consideration given to potential climate shifts.

6. Much research remains to be done in order to improve predictions of the effects of climate change on the environment. For example, improved estimates of future regional climates are needed in order to develop estimates of effects on the environment; vegetation models must be improved and developed for all kinds of vegetation and locations around the world, and agricultural research and analyses must be expanded and integrated to include a wide range of crops/locations and potential responses.

REFERENCES CITED IN SECTION I

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World Meteorological Organization, United Nations Environment P... International Council of Scientific Unions (1986), Report of the Conference on the Assessment of the Role of Carbon Dioxide and Greenhouse Gases in Climate Variations and Associated Impacts, Austria, 9-16 October, 1986 WMO No. 661.

II. EFFECTS ON FORESTS AND VEGETATION

Prepared by:
Jonathan T. Overpeck

A. FINDINGS

1. Climate models predict that a global warming of approximately 1.5°-4.5°C will be induced by a doubling of atmospheric CO_2 and other trace gases during the next 50-100 years. The period 18,000 to 0 yr B.P. is the only general analog for a global climate change of this magnitude. The geological record from this glacial to interglacial interval is a key to understanding how vegetation may change in response to large climate change.

2. The paleovegetational record shows that climate change as large as that expected to occur in response to the equivalent of a CO_2 doubling is likely to induce significant changes in the composition and patterns of the world's biomes. Changes of 2°-4°C have been significant enough to alter the composition of biomes, to cause new biomes to appear and others to disappear. At 18,000 B.P., eastern North American vegetation was quite distinct from that of the present day. The cold/dry climate of that time seems to have precluded the widespread growth of birch, hemlock, beech, alder, hornbeam, ash, elm, and chestnut -- all of which are fairly abundant in present-day forests. Southern pines grew alongside oak and hickory and were limited to Florida.

3. Available paleoecological and paleoclimatological records do not provide an analog for the high rate of climate change that will probably occur over the next century and the unprecedented global warming that is predicted to occur. Previous changes in vegetation have been associated with climates that were nearly 5°-7°C cooler and took thousands of years to evolve rather than decades--the timeframe in which changes resulting from the greenhouse effect are predicted to occur. Insufficient temporal resolution (e.g., via radiocarbon dates) limits our ability to analyze the decadal-scale rates of change that occurred prior to the present millennium.

4. Limited experiments conducted with dynamic vegetation models for North America suggest that decreases in net biomass may occur and that significant changes in species composition are likely. Experiments with one model suggest that eastern North American biomass may be reduced by 11 megagrams per hectare (10% of live biomass) given the equivalent of a doubled CO_2 environment. Plant taxa will respond individualistically to regional changes in climate variables rather than as whole communities.

5. Future forest management decisions in major timber-growing regions may be affected by changes in natural growing conditions. For example, one study suggests that loblolly pine populations are likely to move to the north and northeast into Pennsylvania and New Jersey while its range shrinks in the west. The total geographic range of the species may increase, but a net loss in productivity may result because of shifts to less accessible and productive sites. While the extent of such changes is unclear, adjustments will be needed in forest technology, resource allocation, planning, tree breeding programs, and decision-making to maintain and increase productivity.

6. Dynamic vegetation models based on theoretical descriptions of plant growth must be improved and/or developed for all major kinds of vegetation. In order to make more accurate future predictions, these models must be validated using the geologic record and empirical ecological response surfaces. In particular, the geologic record can be used to test the ability of vegetation models to simulate vegetation that grew under climate conditions unlike any of the modern day.

7. Dynamic vegetation models should eventually incorporate direct effects of atmospheric CO_2 increases on plant growth and other air pollution effects. Improved estimates of future regional climates are also required in order to make accurate predictions of future vegetation changes.

B. INTRODUCTION

1. Importance of Forests

Forests, the most abundant and important vegetation type on land, serve an integral role in the world's ecological and climatological system, covering 35%-40% of the earth's surface, producing 65% of the annual carbon fixation (net primary productivity), and storing over 80% of the world's organic carbon (Solomon and West, 1985). Ecologically and economically, forests serve a number of purposes: they help protect the quality of streams and groundwater supplies, prevent soil erosion, provide fuelwood, timber, paper, chemicals and other forest products, constitute a home for wildlife, and serve as a recreation area for millions of persons.

Globally, the areal extent of forests have been shrinking since pre-agricultural times as deforestation rates have exceeded rates of reforestation. This reduced supply, coupled with expected increases in global demand for wood, may result in critical wood shortages by the end of this century. In addition, deforestation poses enormous ecological and climatological consequences. Loss of forests usually implies some hydrological damage as well as increased soil erosion. Climatologically, deforestation, which causes a net release of carbon into the atmosphere, is estimated to contribute as much as 30% to global warming. A well-known example of this is in the Brazilian Amazon. During the period 1973-1980, efforts to develop the Amazon basin resulted in a 44% decrease in one forest area (Fearnside, 1986). Shown in Figure II-1 is a world distribution of natural vegetation regions.

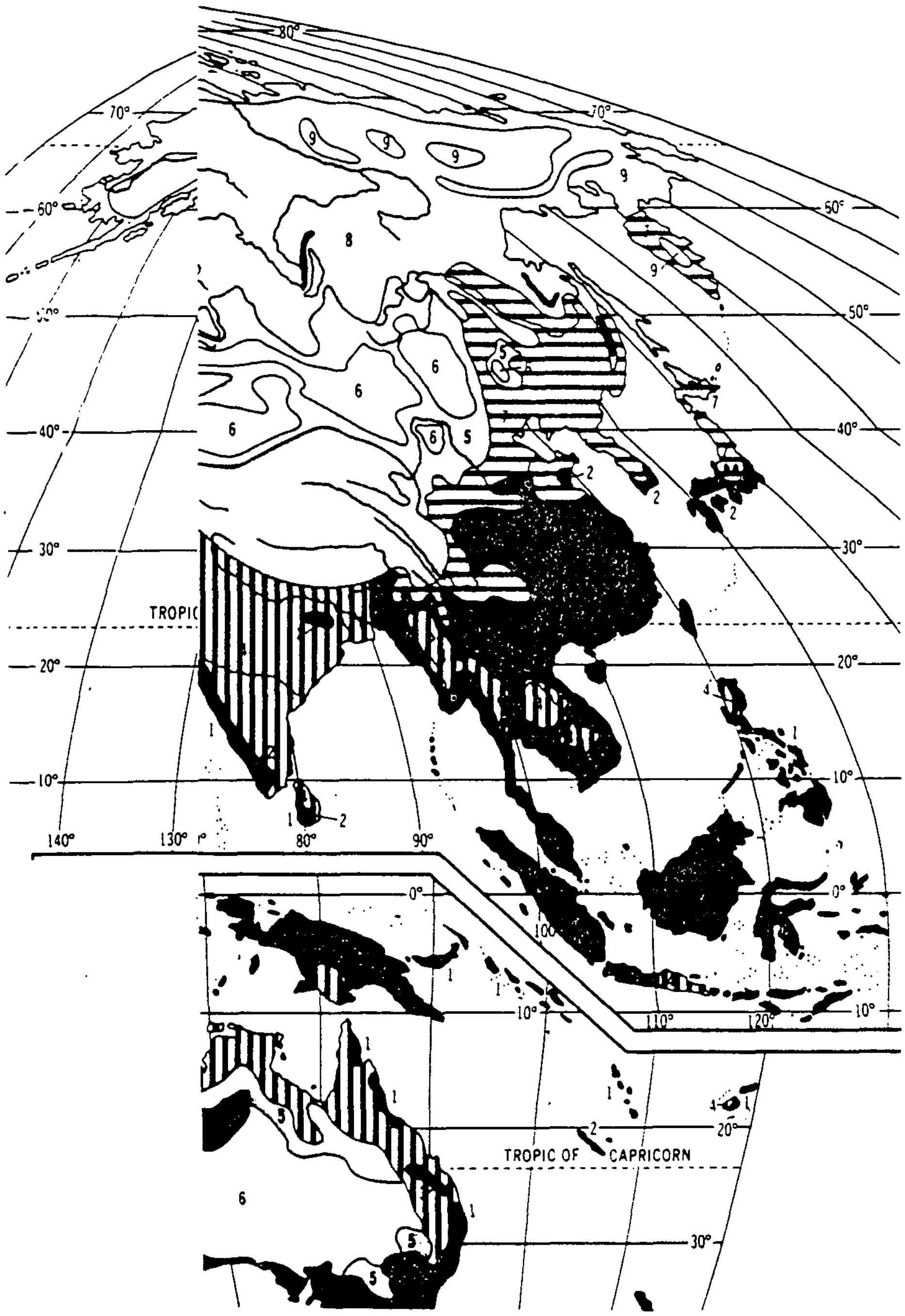
2. Scope of Information in this Section

The overall purpose of this section is to describe how large changes in climate predicted by global climate models discussed elsewhere in this report may affect natural vegetation. It will focus on the changes in vegetational composition and patterns that have accompanied long-term (decades to millennia) changes in climate (Table II-1). It does not discuss the predicted growth enhancement and changes in competitive balance that may result from higher concentrations of CO_2 (Bazzaz, 1986; Bazzaz et al., 1985; Oechel and Strain, 1985; Strain, 1985), nor potential reductions in aboveground biomass and CO_2-induced stress (Fried et al., 1986; Surano et al., 1986), nor does it discuss the short-term (annual to decade) changes in growth rate induced by short-term changes in climate (Fritts, 1976; Jacoby, 1986). These physiological and short-term responses are adequately discussed elsewhere. Additional information about the nature and possible effects of increased atmospheric aerosols and trace gases can be found elsewhere (MacCracken and Luther, 1985a, 1985b; Strain and Cure, 1985; Trabalka, 1985).

The close association between human populations and the terrestrial biosphere requires that we understand how climate change affects natural vegetation and how vegetation change, in turn, influences global climate. The best estimates of future trace-gas-induced climate change are derived from computer models that are sensitive, by way of realistic feedback mechanisms,

FIGURE II-1

Natural Vegetation Regions of the World



Source: Adapted from: Strahler, Arthur N. 1969. Physical Geography, 3rd ed. J. Wiley & Sons, Inc., N.Y.

TABLE II-1

Important Aspects of CO2-Induced Vegetation Change

NATURE OF CHANGE	VEGETATION RESPONSE	TIME SCALE	DATA SOURCE	MODELS	REFERENCES
Increase CO_2	a) Growth response of different species	2 to 10 years	Growth chambers	Plant Physiology	Bazzaz, 1986 Bazzaz et al., 1985 Oechel and Strain, 1985 Strain, 1985
	b) Growth response of different species	2 to 10 years	Tree rings	Response Surfaces	Fritts et al., 1971 Fritts, 1976 Graumlich and Brubaker, 1986 Jacoby, 1986
Climate Change	c) Abundance and range changes in vegetation	10 to 500 years	Pollen	Vegetation climate classification Response surfaces Dynamic vegetation models	THIS REPORT

Source: Overpeck, 1986.

to the directions, magnitudes, patterns, and rates of vegetation change that may result from the climate change itself (Manabe and Wetherald, 1980; Washington and Meehl, 1984; Dickinson, 1986; Hansen et al., 1984; Rind, 1984). Models with and without these feedbacks predict a general global warming of approximately 1.5° to 4.5°C over the next 100 to 200 years (National Research Council, 1983; MacCracken and Luther, 1985a), a magnitude of change unlike any in the past 10,000 years. Only by looking at the vegetation change of the past 18,000 years can we find a past analog for the vegetation change that can accompany a global temperature change as large as that anticipated by greenhouse warming. The geological record of the vegetation change during this glacial to interglacial interval (18,000 to 0 yr B.P.) is sufficient in some continental regions to characterize the rates, patterns, and magnitudes of past vegetation change (Huntley, 1986; Huntley and Birks, 1983; Webb, 1986a, 1986b). This past behavior of the vegetation may serve as a general analog for the types of changes that may accompany trace-gas-induced climate warming.

This section describes this vegetation change and the methods by which fossil pollen data from lakes and mires can be used to obtain quantitative estimates of past climates. Application of pollen-climate calibration functions and empirical ecological response functions will be highlighted. Also discussed are the limitations of the geological perspective and how we might overcome these limitations. Particular emphasis is placed on the need to quantify the rates and nature of response of vegetation to trace-gas-induced climate changes unlike any that have been observed in records of the past. This section does not explore potential shifts in forest pests and pathogens which may also be affected by climate. Finally, because research is just beginning to examine changes on methane emissions which may result from changes in forests, this intrinsic feedback relationship to climate is also not included.

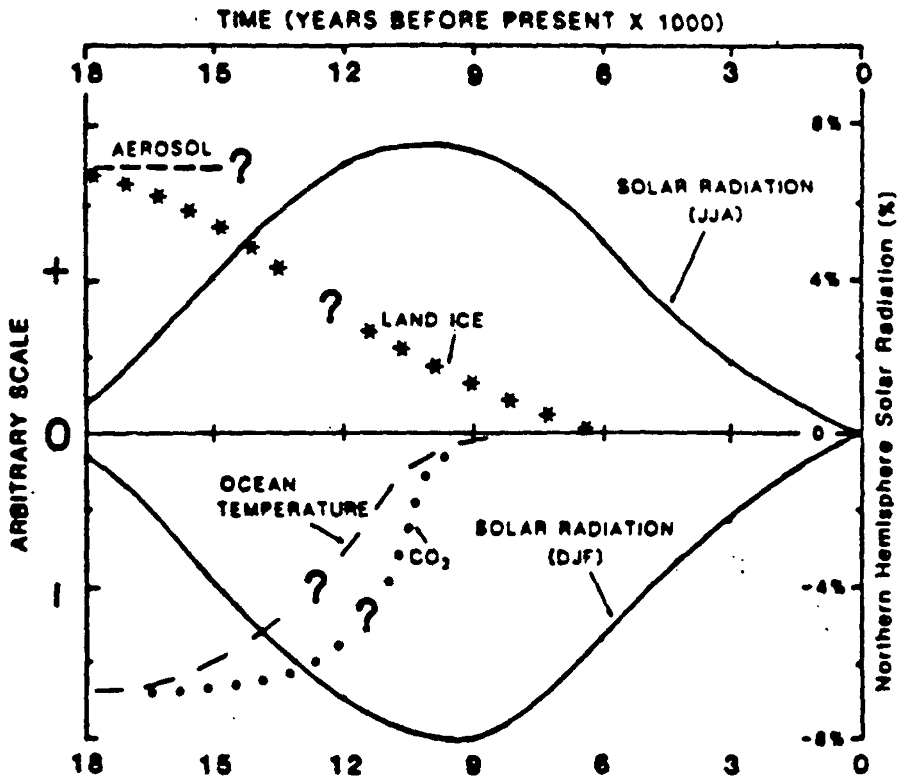
C. CLIMATE-INDUCED VEGEGATION CHANGES OF THE PAST 18,000 YEARS

1. The Nature of Climate Change 18,000 Yr B.P. To Present

Both geological data and climate simulations suggest that the past 18,000 years, spanning a glacial to interglacial period, were characterized by global mean temperature changes of 5°-7°C (CLIMAP, 1976; Manabe and Hahn, 1977; Kutzbach and Guetter, 1986). This change and associated changes in the regional patterns of climate were driven primarily by variations in seasonal radiation that resulted from variations in the earth's orbit (Figure II-2). Northern hemisphere solar radiation was approximately 8% greater in the summer (and, consequently, 8% weaker in the winter) at 9000 yr B.P. than at 18,000 or 0 yr B.P. Dramatically cooler ocean surface temperatures also existed at mid- to high latitudes prior to 10,000 yr B.P., and high-latitude ice sheets persisted as late as 6,000 yr B.P. Numerous studies, including the international efforts by CLIMAP (Climate: Long-range Investigation, Mapping, and Prediction) and COHMAP (Cooperative Holocene Mapping Project) (Webb et al., 1985), have used global networks of paleoclimatic data and climate models to describe the regional patterns of climate change over the past 18,000 years. These studies have highlighted the need to consider how several

FIGURE II-2

Climatic Changes 18,000 B.P. to the Present



Schematic of major changes of external forcing (northern hemisphere solar radiation for June to August and December to February, in percent difference from present, right-hand scale) and internal climatic boundary conditions not explicitly simulated by general circulation models (land ice, ocean temperature, CO2, aerosol -- arbitrary scale of plus or minus departure from present conditions). Question marks indictate uncertainty concerning the exact magnitudes, timing, and, where appropriate, location of the boundary condition changes.

Source: Diagram from J.E. Kutzbach, modified from version in Webb et al., 1985.

climate variables (e.g., seasonal and annual means of temperature, precipitation, etc.) interact to produce vegetation change. The large (5°-7°C) variations of climate that characterized the last 18,000 years contrast markedly with the small variations (less than 1°-2°C) that occurred during the past 9000 years. A mid-Holocene (8000 to 4000 yr B.P.) period of increased mean global temperatures has been cited as a possible analog for a CO2 trace-gas-warmed world (Butzer, 1980; Kellogg, 1978; Webb, 1985), but Kutzbach and Guetter (1986) and Webb and Wigley (1985) have recently raised doubt that this period was actually characterized by significantly higher mean global temperatures. The "Medieval warm period" (ca. 800 to 1200 A.D.) and the "Little Ice Age" (ca. 1450 to 1850 A.D.) were also characterized by small climate variations (Williams and Wigley, 1983).

CO2 trace-gas-induced temperature increases are expected to exceed any hemispheric or global temperature change recorded in instrumental records of the past 100 years (Clark, 1982; Webb and Wigley, 1985; Wigley et al., 1985). An examination of how vegetation changed over the past 18,000 years can thus provide unique clues about the kinds of vegetation change that could be induced by future greenhouse warming. The paleoclimatic data reveal the long-term equilibrium response of vegetation to large climate changes, but they lack the time resolution to reveal the spatial patterns of vegetation change on the time scales of decades and centuries over which future climate change may occur. Models for the short-term disequilibrium response of forests will be aided by knowledge of what the long-term response might be.

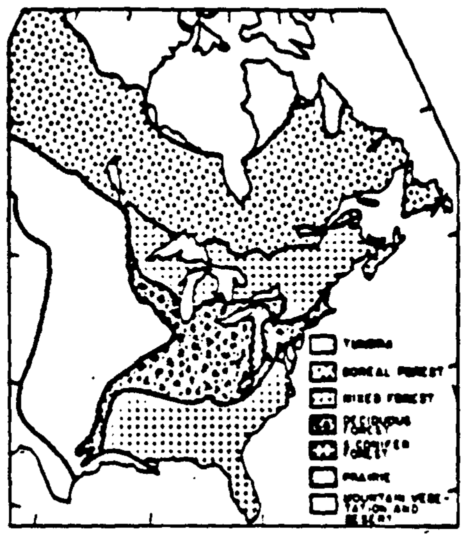
2. Continental-Scale Vegetation Change: 18,000 to 500 yr B.P.

Sufficient pollen data from radiocarbon-dated lake and mire sediments are now available to reconstruct major patterns of the vegetation change that took place over the past 18,000 years. The percentages of different pollen types from large networks of sites can be mapped and contoured to document changes of different plant populations spatially and numerically in response to past climate change (Webb 1986a, 1986b). Drawn at a continental scale, these isopoll maps demonstrate that climate-induced vegetation change can be significant enough to alter the composition of biomes and can actually cause new biomes to appear and others to disappear. To illustrate the types of vegetation change that can be induced by mean global temperature changes in excess of 2°-4°C, isopoll maps are described and interpreted by Webb (1986a, 1986b, 1986c). Webb's inferences regarding the impact of large-scale climate change on natural vegetation are supported by complementary maps produced for part of Eurasia (Huntley and Birks, 1983; Huntley, 1986; Peterson, 1983). Maps for other continental-scale regions are not yet available but are being developed by COHMAP.

A comparison between the spatial distribution of modern biomes (Figure II-3) and the mapped abundances of major pollen types (Figure II-4) demonstrates that mapped pollen percentages are a valuable tool for tracing vegetation change. High values of forb (Artemisia, Ambrosia, other Compositae, Chenopodiaceae, and Amaranthaceae) and sedge (Cyperaceae) pollen coincide with sites in the prairie; spruce (Picea), fir (Abies), and birch (Betula) pollen occur in high abundances at sites in the boreal forest; high

FIGURE II-3

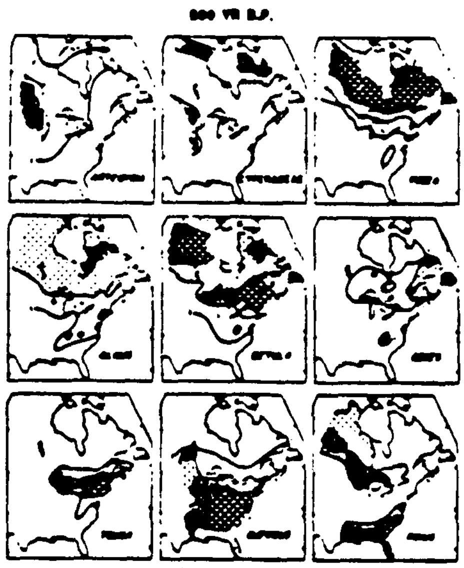
Generalized Vegetation Map for Eastern North America



Source: Webb, 1986b.

FIGURE II-4

Mapped Abundances of Major Pollen Types



Maps with isopolls (contours of equal pollen percentage) for 500 yr B.P. for forb (1,5,10%), sedge (1,5,10%), spruce (1,5,20%), alder (1,5,20%), birch (1,10,20%), fir (1,2,6%), oak (1,5,20%), hemlock (1,5,10%), and pine (20,40%) pollen. Numbers in parentheses give percentages for isopolls. Stippling highlights regions with intermediate (white with black dots) and high (black with white circles) percentages. Forb pollen is the sum of Ambrosia, Artemisia, other Compositae, Chenopodiaceae, and Amaranthacae pollen. The differential scaling of pollen types depends upon the overall abundance of the type in the pollen record. 500-year-old samples were mapped to avoid the biases associated with recent land clearance and settlement.

Source: Webb, 1986b.

values of sedge, birch, and alder (Alnus) characterize the tundra and forest-tundra biomes; sites in the mixed conifer-hardwood forest contain large values of birch and hemlock (Tsuga) pollen in the east and of pine (Pinus) pollen in the west; oak (Quercus) pollen distinguishes the deciduous forest; and the southern pine forests are marked by abundant oak and pine pollen (Webb, 1986a, 1986b). The maps (Figures II-3 and II-4) show that steep gradients in pollen abundances delimit the major ecotones between biomes (Webb, 1986a, 1986b). Maps of other pollen types show similar correspondence with patterns in the vegetation (Bernabo and Webb, 1977).

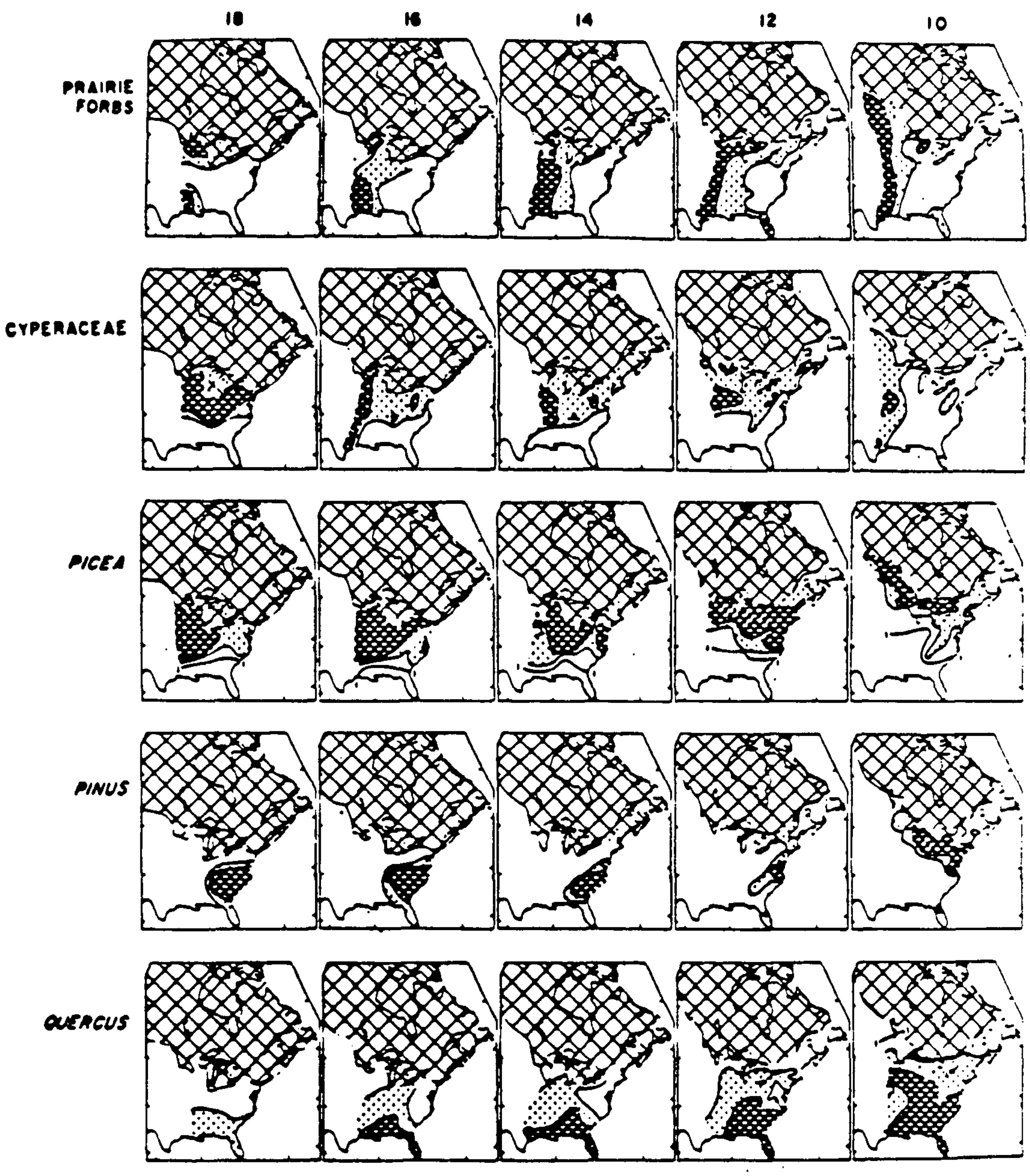
The abundances of five major pollen types were mapped at 2000-year intervals by Webb (1986a) for the period 18,000 to 500 yr B.P. (Figure II-5). Most of the broad-scale vegetational change indicated by these maps was induced by regional macroclimatic change associated with the global climate change that accompanied the shift from glacial to interglacial conditions (Figure II-2). At time scales of 10^3 to 10^4 years, the response time of the vegetation is sufficiently short, when compared with the time scale of climatic forcing, for the vegetation to be in dynamic equilibrium with climate (Gaudreau, 1986; Webb, 1986c). This condition implies that, at the time scale of glacial to interglacial change, vegetation can track changing environmental conditions and produce assemblages of coexisting plant taxa unlike any modern communities. The historical perspective afforded by fossil pollen data thus yields insight into the potential equilibrium response of vegetation to CO_2-induced climate change.

The maps of changing pollen abundances from 18,000 to 500 yr B.P. (Figure II-5) clearly show that the equilibrium response of natural vegetation to large global climatic change can be dramatic in terms of magnitude and pattern of change (Webb, 1986a, 1986b). At 18,000 yr B.P., eastern North America was characterized by vegetation patterns and composition quite distinct from those of the present day. South of the Laurentide ice sheet, an open spruce woodland biome quite different from the modern boreal forest was marked by high abundances of forb, sedge, and spruce pollen. This vegetational community apparently contained little birch or alder. Northern pines grew far south of their modern ranges, and southern pines were limited to growing with oak and hickory in Florida (Watts, 1983). Just as the pollen evidence suggests that a modern-like boreal forest did not exist at 18,000 yr B.P., there is little evidence of a modern-like deciduous forest before 12,000 yr B.P. (Davis, 1983; Webb, 1986a). The cold/dry climate of 18,000 yr B.P. in eastern North America seems to have also precluded the widespread growth of beech (Fagus), hemlock, birch, alder, hornbeam (Ostrya/Carpinus), ash (Fraxinus), elm (Ulmus), and chestnut (Castanea), all fairly abundant in present-day forests (Kutzbach and Wright, 1986; Webb, 1986a, 1986b).

After 18,000 yr B.P., the individualistic response of different plant taxa to climate change produced significant changes in the vegetation of eastern North America. The late-Pleistocene boreal woodland shifted northward and into a more east-west orientation. By 10,000 yr B.P., this biome became a closed forest with the movement of pine populations into the region south of the receding ice sheet, and by 7000 yr B.P., this biome all but disappeared, only to be replaced after 6000 yr B.P. by a boreal forest like that of the

FIGURE II-5

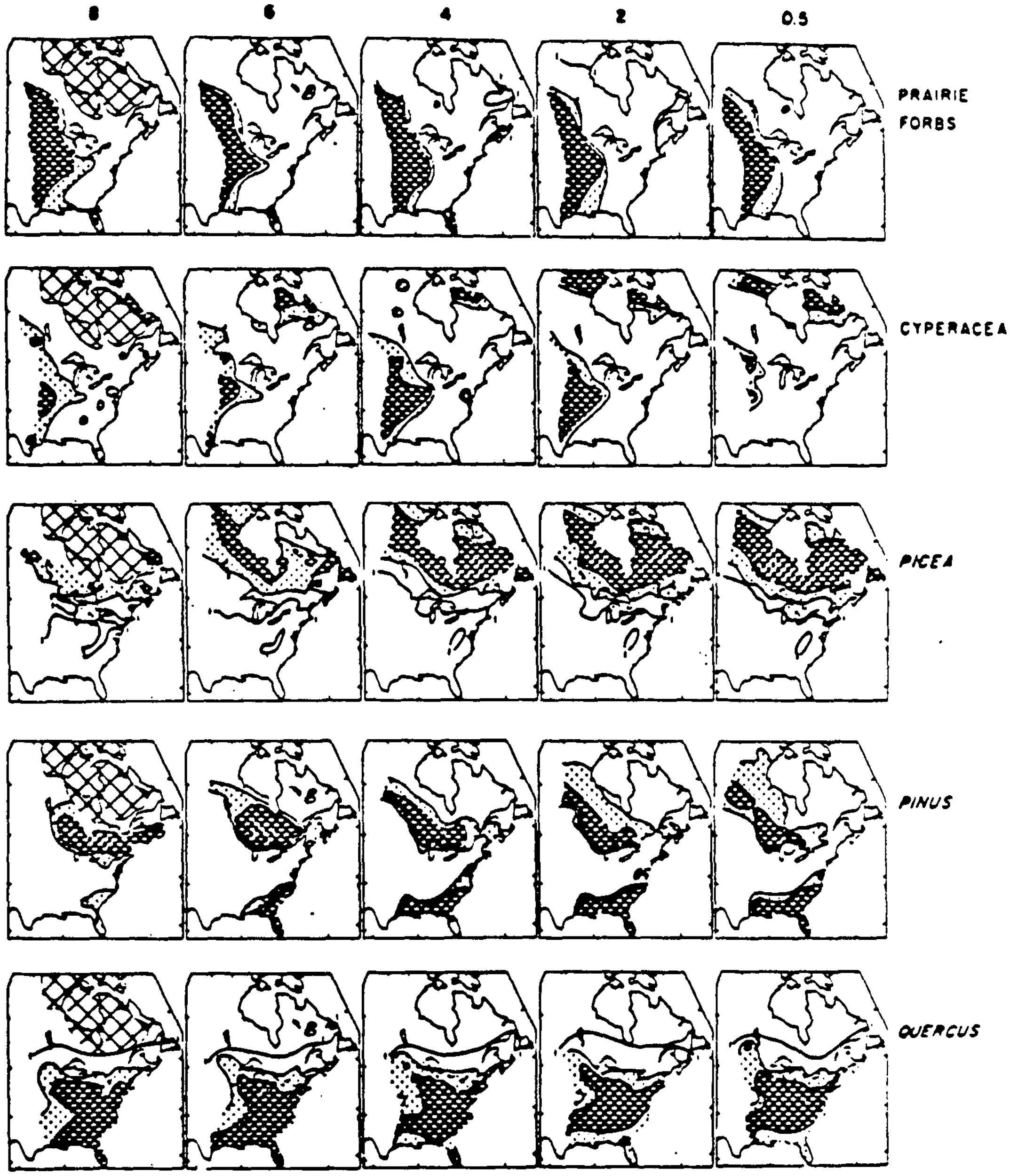
Changing Pollen Abundances from 18,000 B.P. to 500 B.P.



Maps with isopolls for 18,000 yr B.P. to 500 yr B.P. (in 103 yr B.P.) for prairie forbs, sedge, spruce, pine, and oak pollen. See Figure II-3 for labeling of isopolls and stippled regions for each pollen type.

Source: Webb, 1986b.

FIGURE II-5 (Continued)



Maps with isopolls for 18,000 yr B.P. to 500 yr B.P. (in 103 yr B.P.) for prairie forbs, sedge, spruce, pine, and oak pollen. See Figure II-3 for labeling of isopolls and stippled regions for each pollen type.

Source: Webb, 1986b.

present day. Another currently extinct vegetational assemblage produced high abundances of spruce and ash pollen and became widespread by 13,000 yr B.P. It disappeared by 9000 yr B.P. (Overpeck et al., 1985; Wright et al., 1963; Webb et al., 1983). By 10,000 yr B.P., the modern prairie became established in the northern plains, and the southern conifer (pine) forests first became widespread after 6000 yr B.P. This dramatic reshuffling of plant taxa across eastern North America is detailed by Webb (1986a, 1986b, 1986c). Similar data from regions outside North America support the possibility that the magnitude of the equilibrium response of vegetation to a mean global warming of 1.5°-4.5°C could be large, with the likelihood of significant compositional changes in existing biomes and considerable movement of ecotones (Huntley and Birks, 1983; Huntley, 1986; Peterson, 1983; Peteet, 1986).

3. Regional-Scale Vegetation Change: 6000 TO 500 YR B.P.

Before 6000 yr B.P., the climates of the northern hemisphere were influenced to a large degree by the presence of a glacial ice sheet in North America. After this time, the Laurentide ice sheet disappeared and global climate change became largely a function of changing solar radiation at the top of the atmosphere. Variations in the earth's orbit since 6000 yr B.P. have decreased July insolation in the northern Hemisphere by 5% and have increased January insolation by 5% (see Figure II-2; Berger, 1981; Kutzbach and Guetter, 1984; Webb, 1986c). In the upper midwestern United States, this decrease in summer insolation resulted in a southward readvance of the spruce-rich boreal forest, whereas an associated increase in regional precipitation in the Midwest caused forests to advance westward into areas formerly occupied by prairie (Figure II-6; Bartlein et al., 1984). The same orbital forcing induced beech populations to move northward in southern Quebec over distances of 200 km in response to milder winter temperatures at the same time that populations of spruce were able to move 200 km southward in response to cooler summer temperatures (Figure II-7; Webb 1986c). These examples of vegetation change reemphasize the tendency of plant taxa to respond individualistically and to different climate variables. Thus, it seems safe to anticipate that this type of response will typify vegetation change in a future trace-gas-warmed world. It remains to be seen if we can predict quantitatively the rates at which vegetation change will respond to rapid trace-gas-induced climate change or how vegetation will change given future climates unlike any yet recorded.

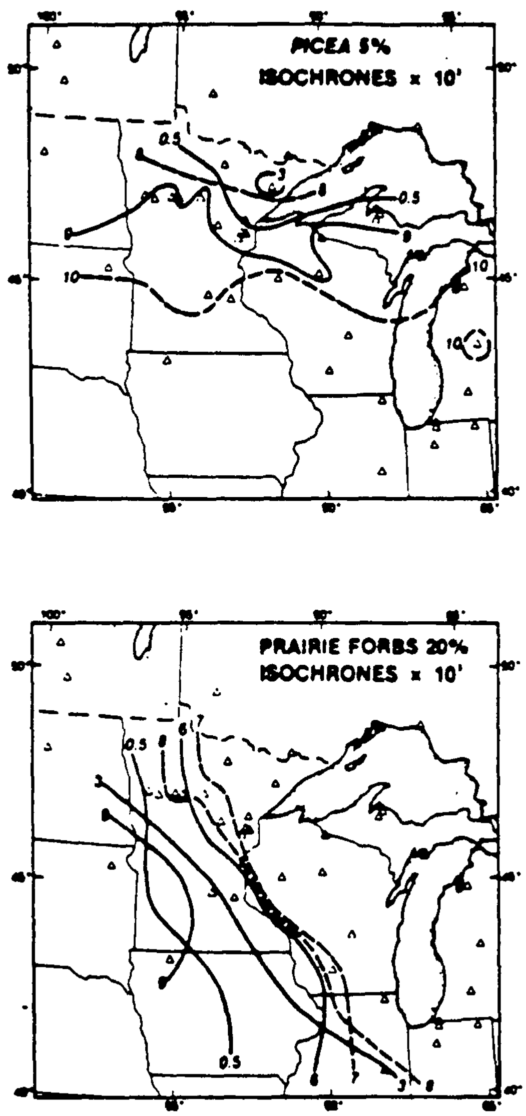
D. POTENTIAL LIMITS TO VEGETATION GROWTH

1. Methodologies for Identifying Vegetation Limits

Fossil pollen data can provide key insights into the manner in which vegetation responds to climate change, and pollen data can also be used to reconstruct past climates. Many paleoclimatic interpretations based on fossil pollen data implicitly or explicitly search for samples of modern pollen that resemble the fossil sample of interest and then reason by analogy that the vegetation and climate associated with the fossil sample were probably similar to those associated with the modern samples. The quantitative nature of pollen data lends itself to going one step further, however, by formulating

FIGURE II-6

Forest Movement in Upper Midwestern U.S.,
10,000 B.P. to 500 B.P.

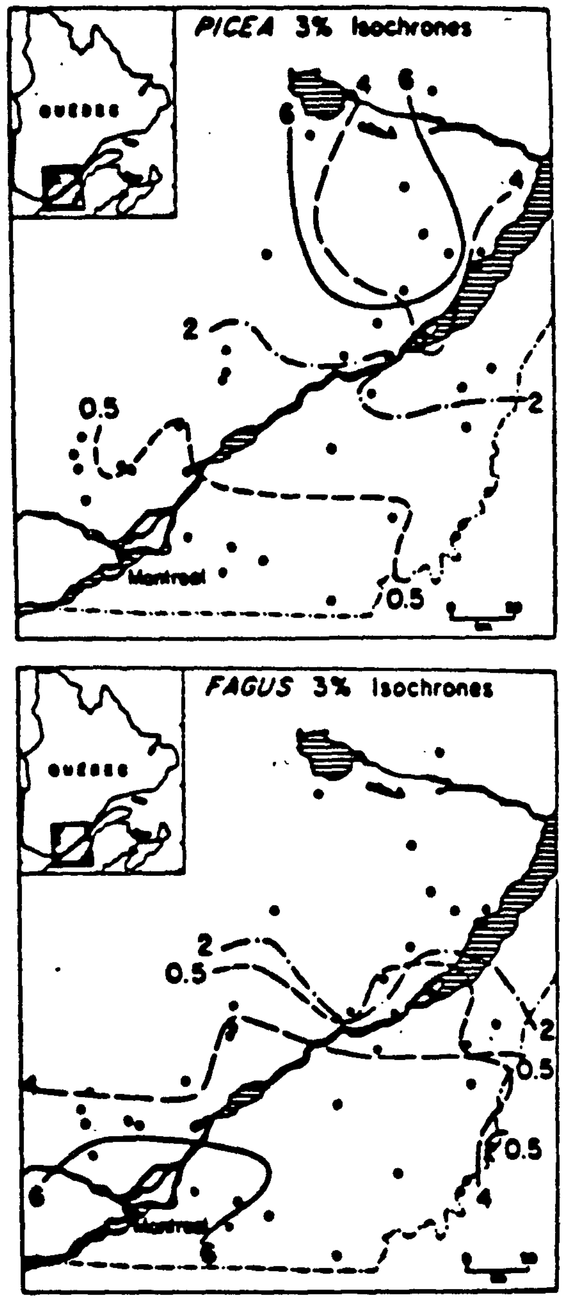


Isochrone maps for 10,000 to 500 yr B.P. (in 103 yr B.P.) from radiocarbon-dated pollen diagrams in the Midwest. The 5% spruce isochrones depict the movement of the approximate southern edge of the boreal forest, whereas the 20% prairie forbs isochrones map the approximate location of the prairie (to the west) -- forest boundary through time.

Source: Webb et al., 1983.

FIGURE II-7

Forest Movement in Southern Quebec: 10,000 B.P.



Isochrone map in 10^3 yr B.P. for the southward extension of the 5% isopoll for spruce pollen and for the northward extension of the 3% isopoll for beech pollen.

Source: from Webb, 1986c.

the functional relationships between the abundances of different pollen types and various climatic variables. Quantitative estimates of past climates are thus possible, as are numerical pollen-climate relationships that can be forward modeled to obtain quantitative estimates of the magnitudes and directions of future vegetation change. The methods described here for pollen-climate calibration are similar to those used in reconstructions of paleoclimate that are based on tree rings (Fritts, 1976; Fritts et al., 1971; Graumlich and Brubaker, 1986).

A robust and straightforward model for calibrating pollen data in climatic terms is the multiple regression model:

$$_{n}C_{1} = {}_{n}P_{m}\,B^{1} + {}_{n}e^{1}$$

where n is the number of samples,
m is the number of pollen types,

$_{n}C_{1}$ is an n vector of values for a particular climate variable,

$_{n}P_{m}$ is an n X m matrix of pollen percentages,

$_{m}B^{1}$ is an m vector of regression coefficients, and

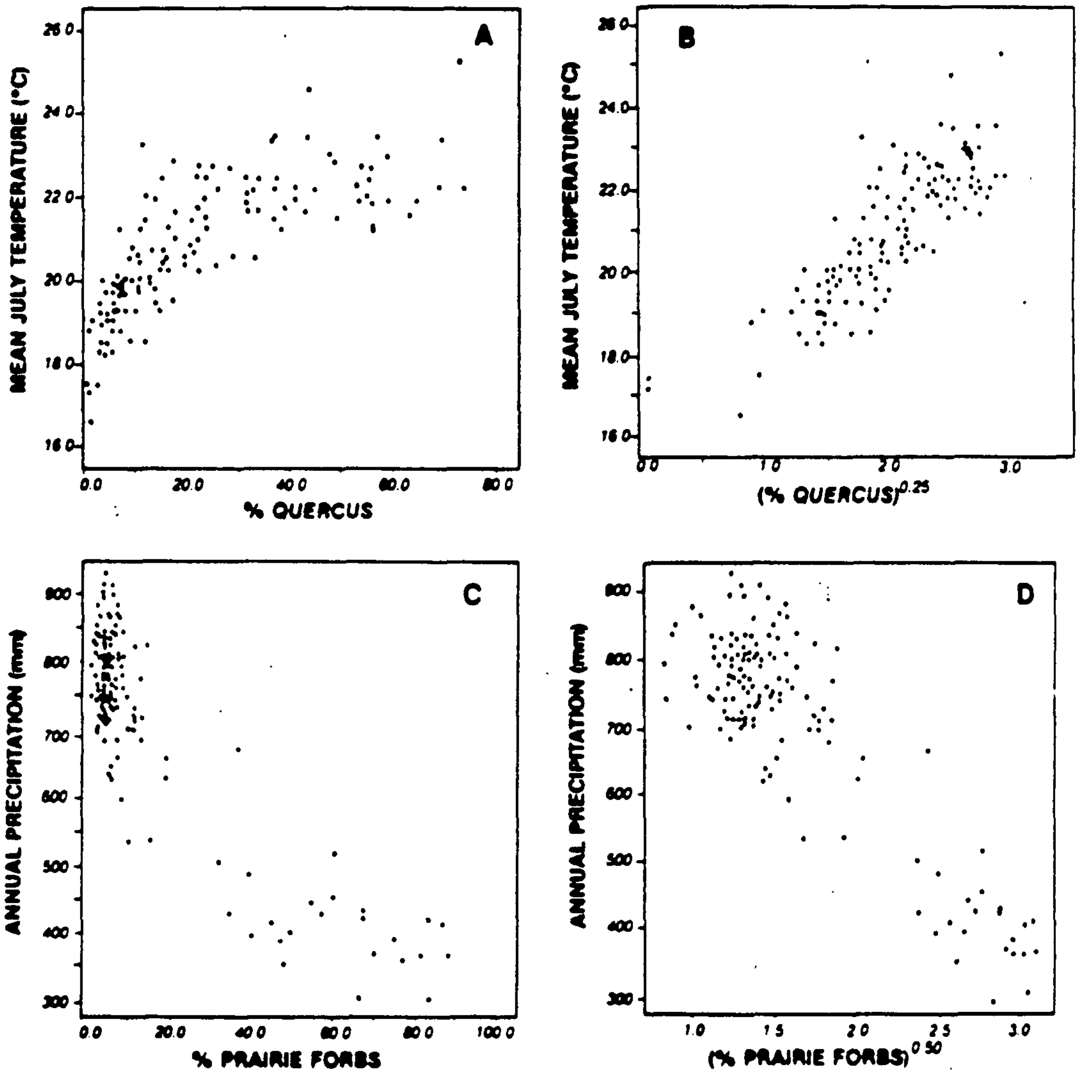
$_{n}e^{1}$ is an n vector of errors.

This approach takes advantage of the strong quantitative relationships that exist between the distribution of plant taxa, as reflected by their pollen, and different climate variables. For example, suitably transformed values of oak pollen are linearly related to mean July temperatures in the Midwest United States, whereas the abundances of prairie forb pollen are related to the amount of mean annual precipitation (Figure II-8; Bartlein et al., 1984). If used with proper statistical considerations (Bartlein and Webb, 1986; Bartlein et al., 1984), this linear regression model allows reliable estimates of past climate values to be generated using regression coefficients (mB1) obtained by regressing modern samples of pollen on the climate values of interest. Statistical calibration procedures of this type are an extension of the transfer function model developed for reconstructing past sea surface conditions (Imbrie and Kipp, 1971; Imbrie and Webb, 1981; Webb and Clark, 1977) and have been used successfully to derive estimates of terrestrial paleoclimate for portions of North America (Bartlein et al., 1984; Bartlein and Webb, 1985) and Eurasia (Huntley, 1986; Peterson, 1983).

Another powerful approach to quantifying the relationship between pollen (vegetation) and climate is the construction of empirical ecological response surfaces. Rather than relating the abundances of a particular group of plant taxa to single climatic variables via a linear model, empirical response surfaces are "non-linear functions describing the way in which the abundances of taxa depend on the joint effects of two or more environmental variables" (Bartlein et al., 1986, p.35). Again, the extensive pollen and climate database available for eastern North America has provided the first

FIGURE II-8

Pollen Versus Precipitation



Scatter diagrams for (A) July mean temperature vs the percentages of oak pollen, (B) July mean temperature vs the percentages of oak pollen raised to the 0.25 power, (C) annual precipitation vs the percentage of prairie-forb pollen, and (D) annual precipitation vs the percentages of prairie-forb pollen raised to the 0.50 power.

Source: Bartlein and Webb et al., 1985.

large-scale test and application for empirical response surfaces (Bartlein et al., 1986). Empirical response surfaces describe the individualistic relation between plant taxa and climate by recasting the geographic distribution of taxon abundance into a surface in climate space. For example, the percentages of spruce and pine pollen exhibit spatial correlation with both mean July temperature and annual precipitation in eastern North America (Figure II-9). When the same percentages are plotted directly against the two climate variables and contoured using appropriate methods, the resulting "surfaces" yield a quantitative description of the optima and range limits of a given taxon, as well as the relative sensitivity (gradient) of the taxon to variation in the two climate variables (Figure II-10; Bartlein et al., 1986).

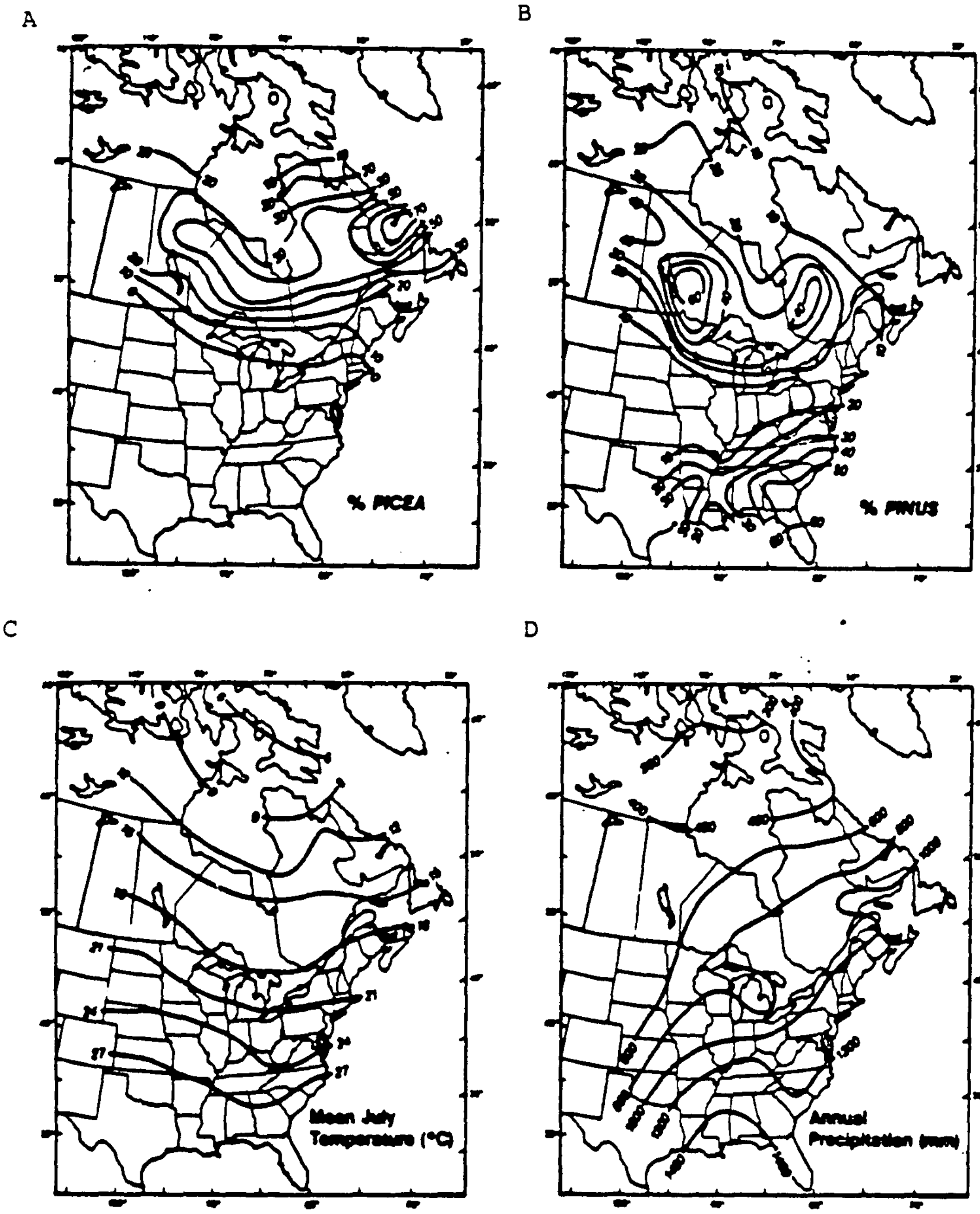
2. Examples of How Temperature and Precipitation Influence Vegetation Growth

Results for the major pollen types of eastern North America support the hypothesis that plant taxa exhibit individualistic responses to different climate variables. The response surface for spruce (Figure II-10a) shows that spruce is most abundant when precipitation exceeds 800 mm/yr and mean July temperatures are less than 15°C. The conditions for the growth of spruce become less favorable with increasing temperatures and decreasing precipitation. The response surface also indicates under what conditions spruce populations are not found (e.g., the range boundaries for spruce) and the portions of climate space, marked by closely spaced contours, in which the abundances of spruce are most sensitive to climatic change. The response surface for pine is more complex than that for spruce, primarily due to the existence of two distinct sets of pine species, one in northeast North America and one in the southeast (Figure II-9a). The southeast pine characterized by optimum abundance at high mean July temperatures (25°-30°C) and high precipitation values (1250-1750 mm/yr), are most sensitive to changes in July temperature, whereas in slightly drier climates (750-1000 mm/yr), pine populations are more sensitive to precipitation. In the driest (250-750 mm/yr) parts of the range for pine, summer temperature again seems to have the most influence on the abundance of pine.

Plants typical of the prairie are highly responsive to precipitation values, although their joint dependence on temperature suggests that annual evapotranspiration may be the best predictor variable for prairie forbs (Figure II-10c; Bartlein et al., 1986). The response surfaces for oak (Figure II-10d) and other major pollen types all reinforce the hypothesis that individual plant taxa have differing sensitivities to different climate variables (Bartlein et al., 1986). Ecological response surface methodology has already begun to show great promise in reconstructing past climates and in helping to validate computer simulations of climate (Bartlein et al., 1986; Graumlich and Brubaker, 1986). Efforts to assess the potential sensitivities of vegetation in response to future climate change should also benefit significantly from the use of response surfaces.

FIGURE II-9

Response Surfaces for Pine and Spruce

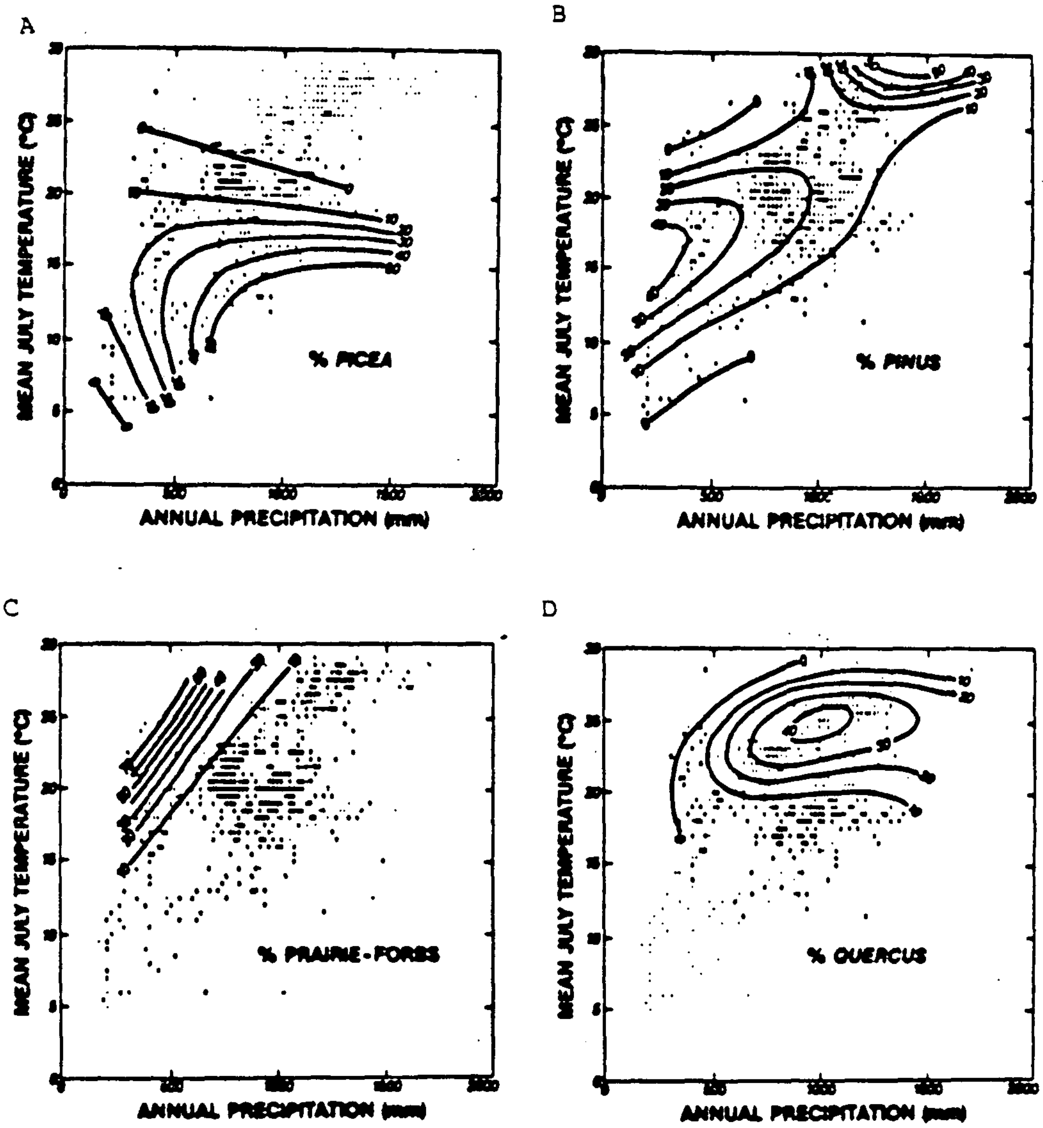


Maps of the distribution of pollen types (spruce and pine) and climate variables (mean July temperature and annual precipitation).

Source: Bartlein et al., 1986.

FIGURE II-10

Ecological Response Surfaces



Empirical ecological response surfaces for spruce, pinus, prairie-forb, and oak pollen showing how the abundances of these taxa vary as a function of mean July temperature and annual precipitation.

Source: Bartlein et al., 1986.

E. PREDICTING THE FUTURE EFFECTS OF CLIMATE CHANGE ON NATURAL VEGETATION

1. Introduction

Analysis of the geological record adds a necessary time dimension to the understanding of vegetation and climate dynamics. Only by examining the geologic record can empirical information be obtained about the magnitude, pattern, and rate of vegetation change that can result from climate change as large (1.5° to 4.5°C) as that anticipated for a trace-gas-warmed world. The period 18,000 yr B.P. to present is most appropriate for study because of the magnitude of change that has occurred over this interval. More recent intervals of time were characterized by smaller magnitudes of climate change, but still form a useful source of information about the nature of vegetation change that can be induced by climate change.

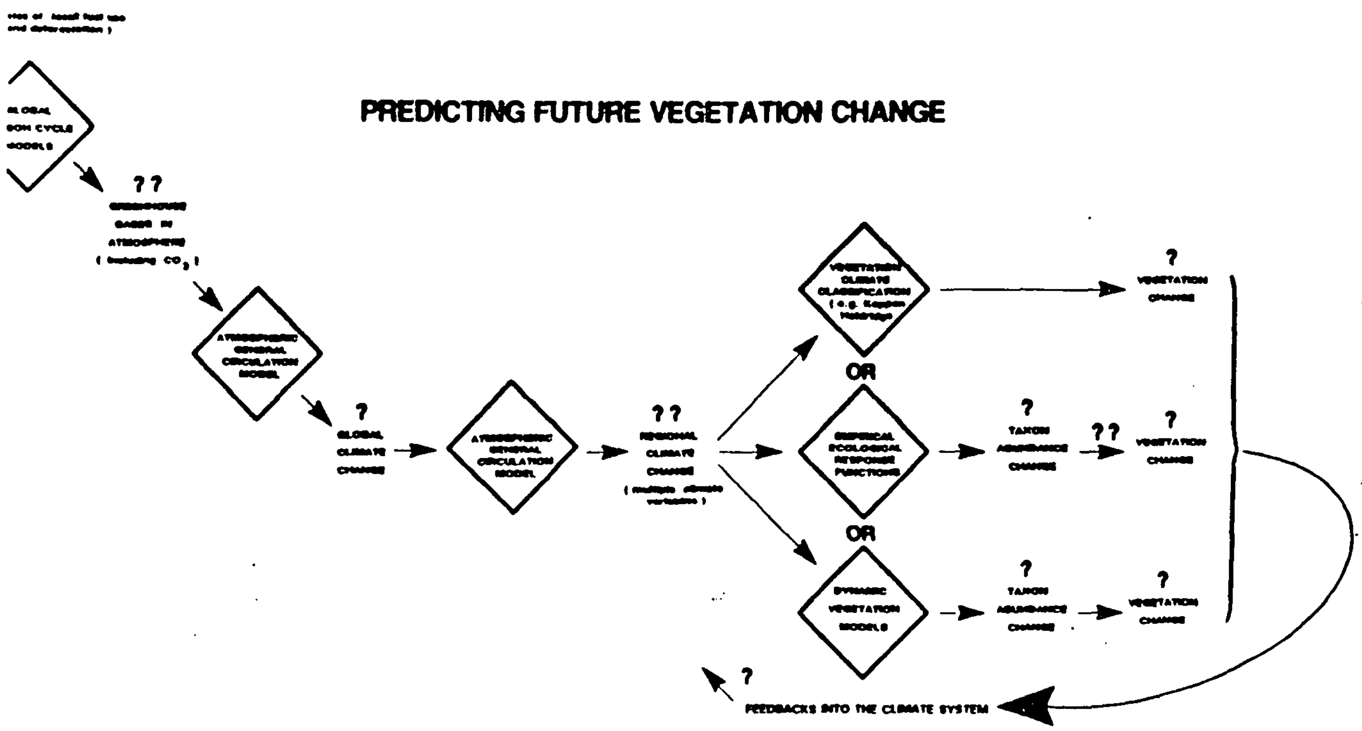
The geologic record of vegetation change is not, however, a perfect analog for use in predicting the changes in natural vegetation that will result from greenhouse warming (Schneider, 1984; Kutzbach and Guetter, 1986). The future configurations of climatic boundary conditions will be distinct from the boundary conditions that gave rise to past patterns of vegetation change. The future dominance of climatic forcing by greenhouse gases and the unique time-dependent response of the climate system to this forcing should lead to patterns and rates of climate and vegetation change that are without precedence in the available geologic record (Webb and Wigley, 1985). This section discusses how we might build on our geological perspective to gain a clearer picture of what lies ahead in terms of climate-induced vegetation change.

2. Uncertainties in Predicting the Regional Macroclimates of the Future

Current knowledge is sufficient to make some generalizations about how vegetation will be affected by trace-gas-induced climate change. Empirical climate-vegetation classification, empirical ecological response surfaces, and dynamic process models of vegetation also make it possible to begin estimating the sensitivity of different vegetation types to various elements of climatic forcing. Before discussing these aspects of predicted vegetation change, however, it is worth considering what we know and need to know about anticipated climate change. The study of past and present climate-vegetation interaction suggests that plant taxa respond individualistically to prevailing regional macroclimatic changes in multiple climate variables. In order to map the actual patterns, magnitudes, and rates of future vegetation change, climatic variables must first be accurately described. Vegetation estimates require reliable climate estimates for the mean and seasonal values for temperature, precipitation, evapotranspiration, and other variables.

A number of steps are required to predict how regional macroclimate will change in the next 50-100 years (Figure II-11). The rates of CO_2 and trace gas emissions must first be estimated. Deforestation, another cause of increasing CO_2 concentrations, at least until 1950-1960 (Houghton et al.,

FIGURE II-11



Flow diagram outlining the steps that go into predicting future vegetation change. Considerable uncertainty is associated with each step. See text for details.

1985; Woodwell et al., 1983), must also be determined (Emanuel et al., 1985a; Olson, 1982). Finally, the nature of global carbon cycling and the interactions between the atmosphere and other carbon reservoirs (e.g., the oceans and terrestrial biosphere) must be modeled more successfully.

These projections of global trace gases must be translated by mathematical models of the climate system. Temperature estimates from these models seem to be least uncertain. A mean global warming of 1.5°-4.5°C is the most cited estimate for atmospheric CO_2 doubling (National Research Council, 1983; MacCracken and Luther, 1985a; Hansen et al., 1981), but recent experiments with independent atmospheric general circulation models (GCMs) suggest that global greenhouse warming will be in the 3.5°-4.2°C range (Schlesinger and Mitchell, 1985). These recent experiments also seem to agree on many features of the global-scale change that will be induced by CO_2 doubling, including a predicted mean global precipitation increase of 7.1%-10.0% (Schlesinger and Mitchell, 1985). In contrast, the most recent experiments (Manabe and Wetherald, 1986) suggest an even greater mid-latitude warming coupled with extended drought. The issue is obviously in doubt.

There is little doubt that the climate changes predicted by recent GCM experiments will cause significant changes in the natural vegetation, but accurate predictions of future vegetation change require better estimates of anticipated regional macroclimate. Unfortunately, more uncertainty must be attached to present GCM predictions of regional climate change than to predictions of global change. Considerable new research must be done before the regional climate patterns can be worked out with confidence (Hoffert and Flannery, 1985; MacCracken and Lüther, 1985b; Schlesinger and Mitchell, 1985). In particular, reliable time-dependent estimates of regional climate change as begun by Hansen et al. (1986) are required before future rates of vegetation change can be estimated. Accurate estimates of future vegetation change are needed, in turn, to improve the ability of climate models to incorporate the effects of vegetation-climate feedbacks (Dickinson, 1986; Rind, 1984). Lastly, the ability of GCMs to simulate modern and past climates can serve as a test of the GCM's ability to simulate future climates. Climate estimates derived from fossil pollen data are necessary for this model validation (Webb et al., 1985).

3. Assessing the Sensitivity of Vegetation to Future Climate Change

Analysis of the geologic record suggests that climate change as large as that predicted for a trace-gas-warmed world is sufficient to cause potentially large changes in the composition and patterns of natural vegetation. A major goal in the effort to predict specific regional vegetation change, however, must be to reduce the uncertainties (Figure II-11) associated with predictions of future regional climate change. Methods to transform regional climate predictions into regional vegetation change also need to be perfected and tested. This section will discuss the utility and limitations of three principal methods for converting climate change into vegetation change (Figure II-11): 1) vegetation-climate classification, 2) empirical ecological response surfaces, and 3) dynamic vegetation models. Although accurate predictions of vegetation change await better estimates of future climate change, the application of these three methods can already begin to delimit what portions of the natural vegetation may be most sensitive to future climate change.

a. Vegetation-Climate Classification

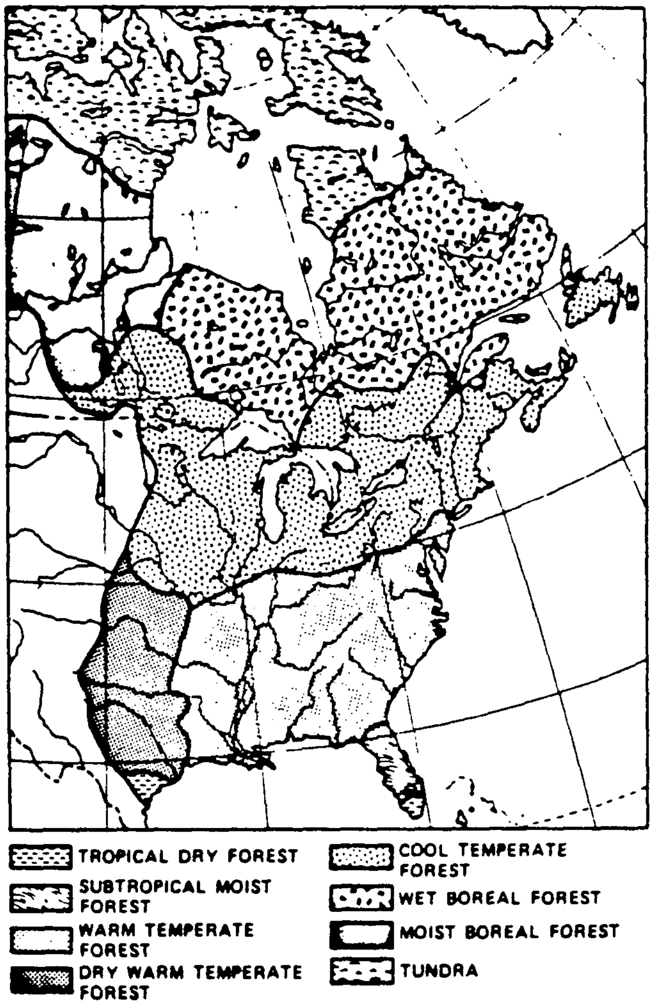
The most widely used method of equating climate change with changes in the vegetation is vegetation-climate classification (Emanuel et al., 1985a; Hansen et al., 1984; Solomon, 1986a, b). These classification schemes, based on Koppen (1936) and Holdridge (1947), use mapped coincidences between major present-day vegetation regions and climatic zones to define a small number (less than 40) of unique global "climate-vegetation zones" (see Figure II-12). Two climate variables, usually related to temperature and precipitation, are typically employed to define the boundaries of the climate-vegetation zones. Predicted variations in these two climate variables can then be inserted into a vegetation-climate classification to get predicted vegetation. This approach assumes that the vegetation-climate relationship captured by the classification is invariant in time and that all possible vegetation-climate combinations are represented on the present surface of the globe.

Solomon (1986b) outlined some of the advantages and disadvantages of the Koppen and Holdridge schemes. Vegetation-climate classification has been widely used primarily because it is simple to implement, global in scale (i.e., compatible with GCMs), and able to reproduce the modern patterns in the vegetation. Emanuel et al. (1985b, 1985c) used simulated climate and the Holdridge classification to predict that climate change induced by CO_2 doubling could cause over 30% of the earth's vegetation to shift from one vegetation type to another. The largest vegetational changes were predicted to occur at high latitudes where the simulated temperature increase is largest and the temperature intervals defining vegetation zones are smallest (Emanuel et al., 1985b). In the absence of projected precipitation changes, tropical vegetation would change least because of small CO_2-induced climate changes, whereas the distribution of subtropical vegetation was expected to change by moderate amounts. In a recent paper, Mather (1986) compared the results from several GCMs to develop global water budgets and estimates of vegetation change (see Figure II-13).

There are several substantial limitations to the use of vegetation-climate classification. Most important, the Koppen and Holdridge schemes ignore much of what is known about vegetation dynamics. The geologic record and empirical ecological response surfaces show that: 1) plant taxa within the vegetation respond individualistically to climate change; 2) plant taxa tend to respond to different mean and seasonal climate variables; and 3) the modern vegetation regions are ephemeral with regard to large climate change. Only the availability of meteorological records limit the types of climate variables that can be used in vegetation-climate classification schemes, but mapped coincidence of climate and vegetation cannot, by itself, imply cause and effect (Solomon, 1986b). All plant taxa do not respond to the same two or three climate variables. It may therefore be difficult to incorporate realistic vegetation-climate relationships into vegetation-climate classification.

FIGURE II-12

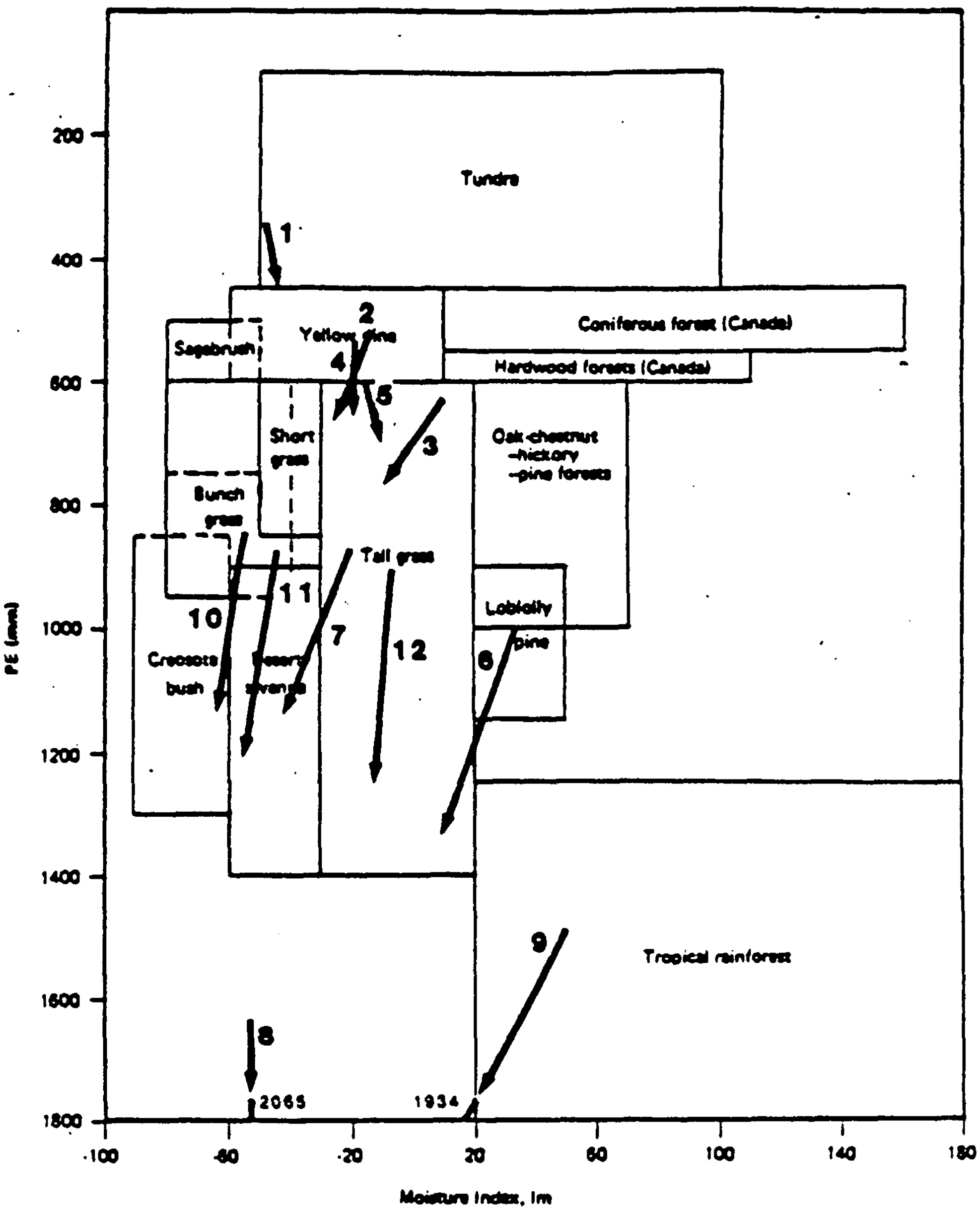
Holdridge Life Zones Mapped



Source: Emanual, W.R., H.H. Shugart and M.P. Stevenson, 1985: Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Climatic Change, 7, 29-43.

FIGURE II-13

Predicted Changes in Natural Vegetation in Selected Regions as a Result of Increased Carbon Dioxide -- GISS Model



1 - North/central Siberia
2 - South/central Canada
3 - Upper midwest (USA)
4 - Pacific northwest
5 - Ukraine (USSR)
6 - Southeast China
7 - Texas and N. Mexico
8 - West/central Africa
9 - Northeast Brazil
10 - Southeast Australia
11 - Southern Africa
12 - Argentina (Pampas)

The individualistic behavior of plants and the ephemeral nature of biomes are ignored by vegetation-climate classification. The vegetation regions of the modern world cannot always serve as analogs for past or future assemblages of plant taxa. Vegetation-climate classifications based on the modern world also lose some credibility when they are used to predict the vegetation change that will occur under climatic conditions unlike any of the present day. This problem of extrapolation, and an equally serious inability to predict the time-dependent rates of vegetation change, are two key issues that must be solved before any method yields accurate estimates of future climate-induced vegetation change.

b. Empirical Ecological Response Surfaces

Another approach to estimating the equilibrium response of vegetation to climate change centers on the application of empirical ecological response surfaces. Unlike vegetation-climate classification, response surface methodology explicitly accounts for the individualistic response of plant taxa to different climate variables (Bartlein et al., 1986). Given suitable plant or pollen and climate data, response surfaces can be used to explore for and to represent the correct combination of climate variables (e.g., mean and seasonal values of temperature, precipitation, evapotranspiration, and other variables) that jointly control the numerical and spatial abundances of a particular taxon. Predicted values can then be used with individual response surfaces to estimate the magnitude and direction of anticipated changes in taxon abundance. For example, the abundances of spruce in North America (Figure II-9a) are likely to be quite sensitive to changes in mean July temperatures where annual precipitation values exceed 800 mm/yr. In addition, a small trace-gas-induced increase in annual precipitation over the midwest U.S. could result in forests expanding into regions now occupied by prairie (Figure II-10c). Steep slopes on response surfaces indicate areas in "climate space" where vegetation is most sensitive to environmental change. Response surface methodology could also be used to estimate future changes in short-term tree growth that might result from traced-gas-induced climate change (Graumlich and Brubaker, 1986).

Empirical ecological response surfaces are designed to model the individualistic response of plant taxa to climate. Unfortunately, it is not practical to construct response surfaces for all of the world's taxa. Even in North America, where much work has been done (Bartlein et al., 1986), it is difficult to estimate response surfaces for more than 10-20 of the dominant plant taxa. For this reason, maps of predicted large-scale vegetation change may be difficult to produce using response surfaces alone. Response surfaces can provide clues about the likely direction of anticipated vegetation change under no-analog climate, but this type of extrapolation must be done with caution. As with vegetation-climate classification, response surfaces are not suited to estimate rates of vegetation change. Empirical ecological response surfaces are still the best way to characterize the individualistic behavior of plant taxa, and as such they deserve further attention and application.

c. Dynamic Vegetation Models

Neither vegetation-climate classification or empirical ecological response surfaces are ideal for describing climate-vegetation interactions under equilibrium conditions. Vegetation-climate classification is flawed theoretically, and it is impractical to construct response surfaces for all the world's plant taxa. In addition, both of these methods fail to deal adequately with extrapolation beyond modern climate space and with time-dependent rates of change. The use of dynamic vegetation models (Figure II-10) may be one way to overcome these inadequacies and eventually to obtain accurate estimates of the magnitude, pattern, and rates of anticipated regional climate change.

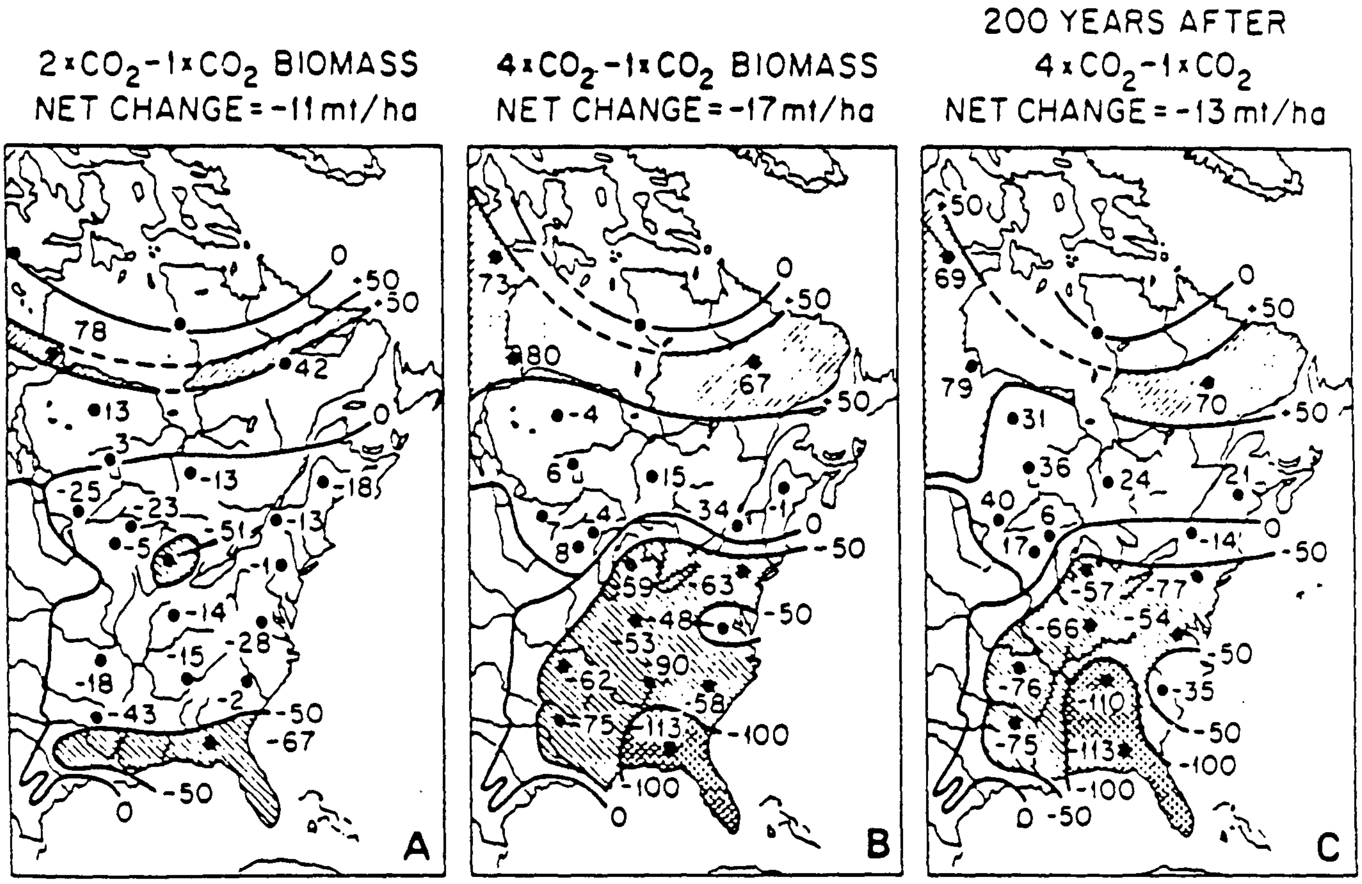
Time-dependent estimates of vegetation composition and structure can now be simulated by models that represent forest dynamics (birth, death, growth, disturbance, competition, etc.) by a series of stochastic and deterministic equations. These models have been most widely developed to simulate the dynamics of very small (less than 1 ha) forest patches (Davis and Botkin, 1985; Shugart, 1984; Solomon, 1986a). More recently, new efforts have been initiated to model larger scales of vegetation and to incorporate better representations of landscape heterogeneity into the model (Prentice et al., 1986).

Plant growth in dynamic vegetation models is usually determined by climate response functions for each taxon being simulated. These response functions are keyed heavily to empirical growth data, but the current trend is to move away from an empirically based representation of climate-vegetation interaction to a more process-oriented theoretical basis. Models built on this theoretical basis will be better suited to simulate vegetation change under climate conditions unlike any of the present day. Just as climate models (e.g., GCMs) can be validated, dynamic vegetation models can be tested against the record of past vegetation change (Solomon and Shugart, 1984; Solomon and Webb, 1985). In particular, it is important that dynamic vegetation models be able to simulate the individualistic behavior of taxa through time. Models that can reproduce the magnitudes, patterns, and rates of change observed in the geological record can then be used to infer vegetation change in a trace-gas-warmed world. Dynamic vegetation models should also be able to reproduce the vegetation patterns that are on the modern landscape.

Several experiments with GCM output coupled with dynamic vegetation models have suggested that future climate-induced vegetation change will be significant in North America (Solomon, 1986a, 1986b; Solomon et al., 1984). As shown in Figure II-14, Solomon's simulation of 21 sites in eastern North America resulted in a loss of live, aboveground stand biomass of 11 megagrams per hectare (10% of live biomass) given a doubled CO2 scenario. Shown in Figure II-15 are results of simulated dynamics at three sites: a boreal forest in west central Ontario, a coniferous-deciduous transition forest in northwest Michigan, and a deciduous forest in east central Tennessee (Solomon and West, 1986). At the boreal site, when CO2 doubling is reached, biomass declines for 50-75 years as warming kills off large boreal forest species.

FIGURE II-14

Carbon Storage Dynamics

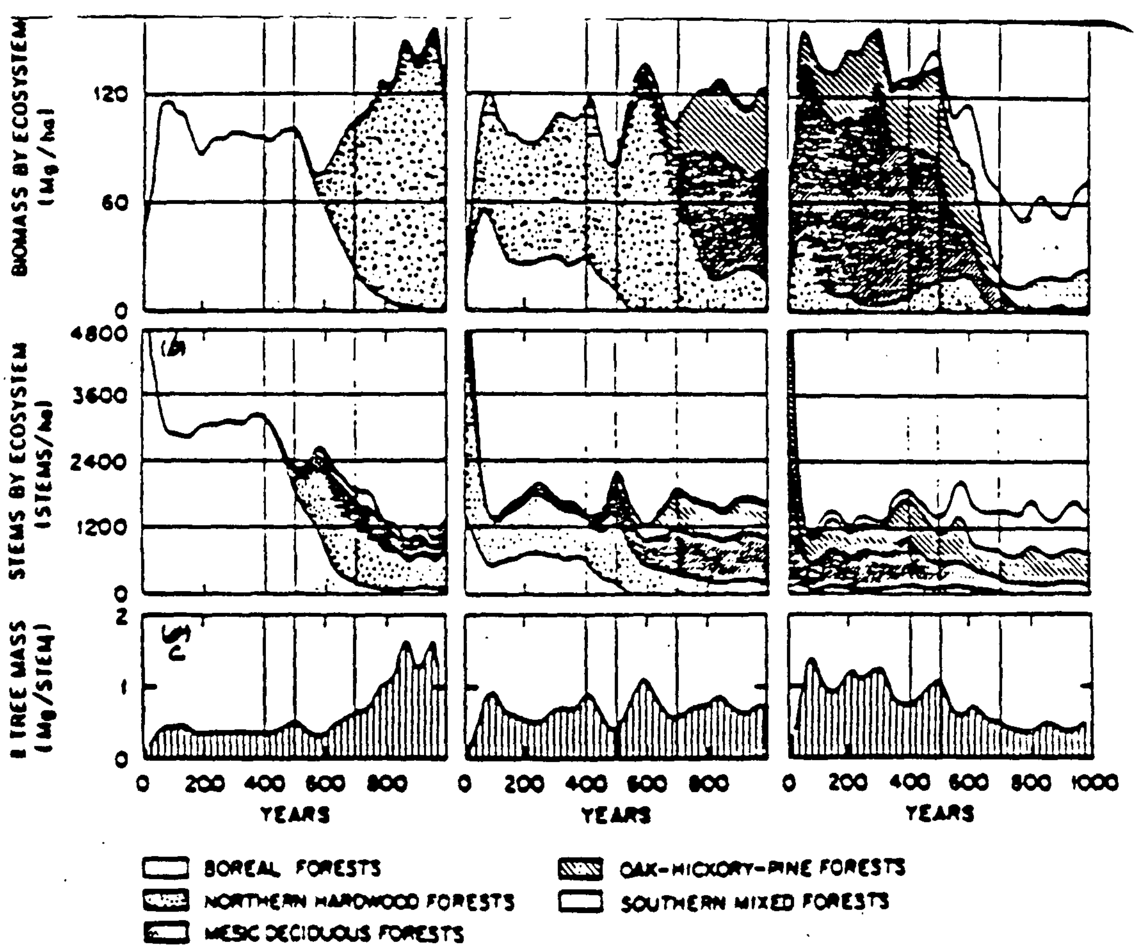


Carbon storage dynamics (in metric tons per hectare [mt/ha]) simulated at 21 sites in eastern North America. Maps show differences between carbon storage simulated with contemporary climate and that simulated with 2 x CO2 climate (A), 4 x CO2 climate (B), and 200 years after 4 x CO2 climate stabilizes (C).

Source: Solomon, in press.

FIGURE II-15

Simulated Dynamics at Sites in Boreal, Transition, and Deciduous Forests



This loss of biomass is eventually recovered as new northern hardwoods begin to grow in the plot. Similarly, in the transition forest of Michigan, biomass losses occur with CO_2 doubling and are recovered later with the growth of northern hardwoods, then decline again, then rise again with the onset of other species more adapted to a warmer climate (quadrupled CO_2). Unlike the first two simulations, the deciduous forests of Tennessee show a permanent loss of dense forest.

For a number of reasons, these results must be considered preliminary. Solomon (1986b) argues that response to climatic variance incorporated into dynamic stand models, must also be incorporated into the GCMS. Empirical response functions based on pollen, tree-ring, and forest inventory data may also lead to better climate response functions and more realistic simulations. In several experiments (those of Solomon, et al., 1982; Davis and Botkin, 1985; Solomon et al., 1984) the rates at which vegetation can respond to climate change have begun to be explored. These experiments suggest that a vegetational response to trace-gas-induced climate change could be observed in less than 100 years. Improved dynamic vegetation models coupled with time-dependent climate simulations of future trace-gas-induced change should provide a clearer picture of how vegetation will change in the future.

d. Potential Climate Change and Forest Management

In June 1984, forest scientists, climatologists, forest industry executives, and others, met in Boulder, Colorado, at a conference sponsored by the National Forest Products Association, the Society of American Foresters, The Conservation Foundation, and the U.S. Environmental Protection Agency. The objective was to exchange information on CO_2 accumulation, possible changes in climate, potential effects on trees and forest ecosystems, and to explore forest management options and identify research needs. In a forthcoming book edited by Shands (1986), a number of authors review the effects on the forest product industry. They point out that while climate change could disrupt ecosystems and alter growing conditions, whether forest productivity decreases or increases will depend to a substantial degree on how forest managers respond to environmental changes. They suggest that if atmospheric concentrations of CO_2 and the greenhouse effect change natural growing conditions, "adjustments will be needed in forest technology, resource allocation, planning, and decision-making to maintain or increase productivity."

Just how climate change might affect important commercial species in two of the nation's major timber-growing regions is explored in papers by Leverenz and Lev (1986) and by Miller (1986) in Shand's book.

Leverenz and Lev project distribution under a scenario of doubled atmospheric CO_2 for six western U.S. tree species -- ponderosa pine, Douglas-fir, western hemlock, western larch, lodgepole pine, and Englemann spruce. Their analysis is derived from information on physiological changes in plants, induced by accumulating CO_2, combined with rising temperature and water stress. These projections are sensitive to assumed responses to the balance between precipitation and evaporation on a site and the assumed chilling requirements of different species.

In brief, Leverenz and Lev make the following predictions: Ponderosa pine will increase in area and importance in California and in the Oregon Cascade Mountains, but decrease in range on the east slope of the Rocky Mountains from Canada to Mexico. Douglas-fir either maintains or expands its importance throughout most of it commercially significant range, while decreasing in importance on southern and coastal sites and on the east slope of the Rocky Mountains. Western hemlock's range decreases in northern Idaho and east of the Willamette Valley in Oregon but increases in importance along Oregon's coast. Western larch generally increases in importance but decreases in area in Washington and Oregon. Lodgepole pine is not affected significantly, while Engleman spruce declines in acreage over its entire present range.

Miller found that loblolly pine would be affected significantly in terms of both range and productivity (Figure II-16). Its range is likely to move to the north and northeast, into eastern Pennsylvania and New Jersey, and shrink in the west, withdrawing into central Arkansas. The total range of the species is likely to increase from the present 344,000 square miles (139,271 hectares) to 385,000 square miles (155,870 hectares). However, they project a net loss of commercial loblolly lands because a large proportion of the new range will be in highland sites less accessible and less productive than present loblolly sites in the Coastal Plain.

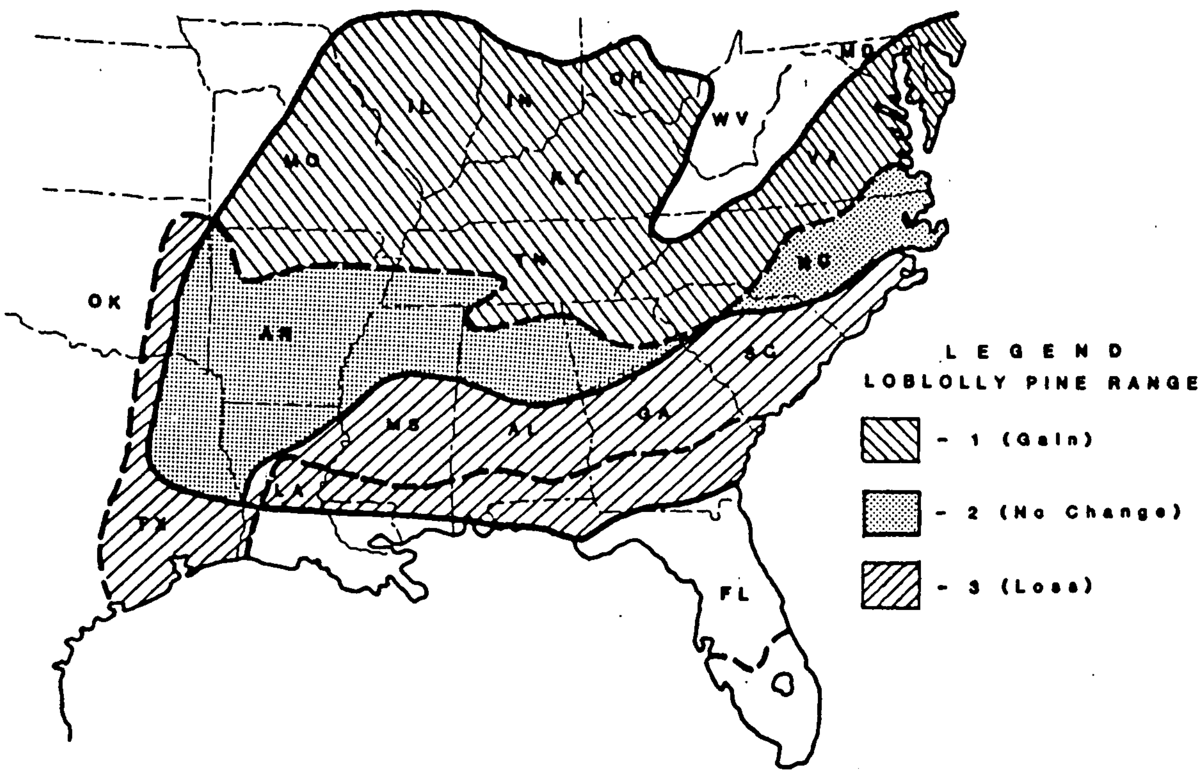
In this same volume, papers by Woodman and by Rose et al. look at the situation from an industry perspective. Under the doubled CO_2 climate scenario, Rose and colleagues conclude that industry strategies are unlikely to change significantly. In the Lake states, shortfalls of aspen can be covered by other presently underutilized hardwoods and aspen stand residues. In the Southeast, however, climate change could have a major impact on supply, since shortfalls are currently predicted, irrespective of climate change, in both softwoods and hardwoods by the year 2030. However, companies now are reevaluating their land ownerships and management programs, and climate change scenarios are not likely to affect current strategies to deal with the expected supply shortfall.

As for the management of Douglas-fir and western hemlock on the coast ranges and west slope of the Cascade Mountains in Washington and Oregon, Woodman too foresees no major changes in management as a result of climate changes attributable to a doubling of atmospheric CO_2. He notes that the transition from harvesting of old growth natural forests to the tending of man-established stands will be complete in the not-too-distant future. The trend now underway toward prescribing management practices on the basis of site productivity--with intensified management of stands on highly productive sites--should allow forest managers to adjust to gradual change in a timely fashion. Nonetheless, Woodman expects management problems in forest regeneration at an affordable cost in areas where water stress occurs.

In the final paper of Shand's book, Lee and Kramer argue that by anticipating changes that might occur because of rising CO_2, "the forestry community can avoid surprises, identify alternatives and seek to temper decisions with technological information." Lee and Kramer argue that with or without CO_2-induced climate change, research on problems of CO_2 accumulation

FIGURE II-16

The Projected Changes in Loblolly Range Asjumia, Doubled Atmospheric CO2



Source: Shands, 1986.

and climate change will help answer a number of contemporary questions about how trees respond to environmental stress and how adverse effects can be mitigated. They argue that increasing atmospheric CO_2 is affecting tree growth now; that the forest products industries should not consider it a distant problem to be addressed sometime in the future; that the direct effects of CO_2 buildup should be separated, for research purposes, from indirect, climate change effects; and that plant physiologists and forest scientists should concentrate on understanding how current weather extremes affect the physiological processes that control tree growth.

F. CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Table II-2 lists the primary knowns, uncertainties, and unknowns that must be resolved so that responses of forest ecosystems to climate changes induced by CO_2 (Solomon and West, 1985) can be evaluated. Despite these large uncertainties, a number of inferences can be drawn from the research to date. Although no single global climate change of comparable magnitude and rate is apparent in the geological record, the period 18,000 yr B.P. to the present can serve as a basis for understanding how vegetation can respond to a climate change as large as that expected in the next 100-150 years. Well-dated paleovegetation data spanning 18,000 to 0 yr B.P. from a global network of sites are presently being assembled by COHMAP. Available pollen data from North America and Eurasia show that the overall vegetation change associated with this glacial to interglacial interval was significant and that plant taxa responded individualistically to changes in multiple climate variables. The patterns and composition of biomes are not necessarily constant in time. These observations must be incorporated into any model that is expected to yield accurate estimates of future vegetation change.

The geological record holds additional promise as a baseline for understanding how vegetation responds to climate change. Temporal resolution is not presently sufficient to study the past response of vegetation to rapid (within 10-100 years) climatic change. Improved temporal resolution, independent paleoclimatic and paleovegetation data, and improved methods for the quantitative analysis of time series could make it possible to study the time-dependent magnitude, pattern, and rate of vegetation change following rapid climate change (Overpeck, 1986). These empirical studies of vegetation change would provide an additional basis for the validation of models that are used to predict vegetation change. The geological record thus offers a wide range of experience on which to build and test models of future vegetation change.

The time-dependent nature of the anticipated climate-induced vegetation change must be studied using dynamic vegetation models. Current versions of these models need improvement and models remain to be developed for most of the world's vegetation. At the present time, little can be said about the potential climate response of low-latitude forests. We know that vegetation change occurred over the glacial to interglacial interval (Peteet, 1986), but too few basic ecological data exist for these low-latitude vegetation regions. Empirical ecological response surfaces remain to be exploited to their full potential. Dynamic vegetation models should be tested against response surfaces as well as against records of past vegetation change.

TABLE II-2

PRIMARY KNOWS, UNCERTAINTIES AND UNKNOWNS REQUIRING RESOLUTION IN ORDER TO APPRAISE FOREST ECOSYSTEM REPSONSES TO CLIMATE CHANGE INDUCED BY CO_2

ISSUES	KNOWNS	UNCERTAINTIES	UNKNOWNS
A. ISSUES DETAILED IN OTHER SOA REPORTS			
1. Carbon Cycle Issues			
a. Atmospheric CO_2 Accumulation	Atmospheric CO_2 concentration is rising	preindustrial CO_2 value	Time when doubled and maximum CO_2 will occur. Maximum future CO_2 concentration.
	Seasonal CO_2 amplitude is increasing	Source of increasing amplitude	Significance of amplitude changes to carbon cycle, vegetation, climate effects.
	Land use (forest clearance) contributes to atmospheric CO_2	Rates at which land-use generates atmospheric CO_2 increases	Future contribution to CO_2 by land use.
b. Atmospheric CO_2 Depletion	Oceans are the primary global atmospheric CO_2 sink	Rates at which CO_2 crosses the ocean-atmospheric interface by geographic region	Internal circulation of oceans by geography that controls up and down welling of CO_2 rich and CO_2-poor water masses.
	Terrestrial biota is a secondary global atmospheric CO_2 sink	Current areas and amounts of carbon stored in terrestrial biosphere	Future carbon source, sink, and storage properties of terrestrail biosphere
2. Climate Effects Issues			
a. Geography of Climate Change	Greater warming at poles than at equator	Intensity of latitudinal temperature differences	Local and regional temperature shifts
	Changes will occur in geography of precipitation	Geography of precipitation	Local and regional precipitation shifts
b. Variance from Mean Climate Changes	Variance may or may not change	Presence or absence of variance changes from current geography	Amount of variance change, if any, locally, regionally, globally
c. Temporal Chronology	Climate will change over time	Rate and nature (step function, climate continuou slinear, etc) of climate change	Temporal chronology of climate change
d. Seasonal Features of Climate Changes	Greater warming in winter than in summer	Amount of seasonal warming	Local and regional change in seasonal warming
	Quicker warming in summer than in winter	Time difference between summer and winter rates of warming	Local and regional time difference between summer and winter warming

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TABLE II-2
(continued)

PRIMARY KNOWS, UNCERTAINTIES AND UNKNOWNS REQUIRING RESOLUTION IN ORDER TO APPRAISE FOREST ECOSYSTEM REPSONSES TO CLIMATE CHANGE INDUCED BY CO_2

ISSUES	KNOWNS	UNCERTAINTIES	UNKNOWNS
3. Vegetation Effects Issues			
a. Applicability of Single Factor Greenhouse Experiments to Multifactor Field Situations	Published reports on single-factor experiments show increase photosynthesis, decreased water use, increased leaf area, increased dry weight, increased photosynthesis in shade	No published reports on multiple factor experiments that realistically simulate field conditions; whether mature tress and ecosystems will response similarly	Amount, if any of response in multifactor situations; quantitative importance of offsetting (canceling) factors to tree growth
b. Applicability of Short Duration (hour, day) Fumigations to Long-Term Tree Growth	Published reports on longer term (months, seasons) experiments show short-duration effects decline and/or disappear	Will field-grown trees cease responding to CO_2 increases	How much, if at all, will field-grown trees acclimatize to enhanced CO_2
c. Applicability of Experiments on Herbaceous Annuals, Leaves, Branches, and Tree Seedlings to Mature Trees	Effects in 3A are found in these plants or plant parts	Will mature trees respond as do plants or plant parts tested; if so what is the nature of forcing function (linear, logaritmic, etc.)	Amount, if any, by tree species or by other functional unit (shade tolerance, growth rate, etc.) that trees will respond as do other plants or plant parts
d. Applicability of Experiments in 3a, 3b, 3c, to Regional or Global Vegetation	The few trees and fewer species examined to date have declined in growth, while CO_2 has increased in concentration	Has the current 30% CO_2 increase affected tree growth; importance of climate change and other pollutants during same period in depressing tree growth.	Will future changes in climate and atmospheric pollutants negatively affect tree growth; if so, how much compared with possible CO_2 effects
B. ISSUES DETAILED IN THIS REPORT			
1. Seedling Survival	Temperature, precipitation variance control initial seedling survival	Will temperature and precipitation variance change in the future	By how much, if any, will variance in temperature and precipitation change
	CO_2 enchancement, below current forest floor concentrations, increases vigor, productions, biomass, leaf area, and drought-tolerance differentially by species	Will CO_2 enhancement above current forest floor concentrations have the same effects	Will CO_2 increase have long-term effects on massive mortality and, if so, which species will be favored
	Pathogens and predators destroy seeds and seedlings	Will pathogen and predator effects be different in the future	Which species will be favored and by how much if predator and pathogen effects occur

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TABLE II-2
(continued)

PRIMARY KNOWS, UNCERTAINTIES AND UNKNOWNS REQUIRING RESOLUTION IN ORDER TO APPRAISE FOREST ECOSYSTEM REPSONSES TO CLIMATE CHANGE INDUCED BY CO_2

ISSUES	KNOWNS	UNCERTAINTIES	UNKNOWNS
2. <u>Sapling and Tree Growth</u>	Climate variance controls geographic ranges of mature species	Specific climate variables and their variance values controlling the cold, warm, and dry parts of each species' geographic range	Future local and regional climate variances; future effects of CO_2 on responses of species to climate variance; future geographic range of species
	Climate variance controls annual growth rates	Specific climate variables and their variance values	Future local and regional climate variances; resultant shifts in competitive advantages among species
	Nutrients for growth depend on decomposition rates	Will decomposer populations change nutrients available because of warming of soils	Future amount of nutrients available because of changes in decomposer activities due to warming
	Root respiration depends on soil temperature, water, and oxygen availability	Will root respiration increase of climate change	If root respiration changes, will it counteract increased production from CO_2 if such increases occur
3. <u>Death and Reproduction</u>			
a. Senescence	Senescent trees die from stresses that younger trees can survive	If climate change continuously, will trees become prematurely senescent because of the additional stress of this continuous change	Will CO_2 induce vigor and prolong tree life and, if so, which species will be most affected and which will be least affected
b. Catastrophis Age-Independent Mortality	Wildfire frequency and intensity depends on climate, fuel, and time since last fire	Geographic change in wildfire frequency and intensity due to future climate change	Local, regional changes in the temperature and precipitation extremes that control fire frequency and intensity
	Windstorm and flood damage depends on frequency of rare climate extremes, topography, land-use	Geographic change in land use due to climate change	Local, regional distribution of future rare precipitation, wind extremes
	Pathogen, insect epidemics occur rarely	Climate dependency of pathogen, insect epidemics	Will climate control pathogen and insect epidemics and, if so, how

*** DRAFT FINAL ***

TABLE II-2
(continued)

PRIMARY KNOWS, UNCERTAINTIES AND UNKNOWNS REQUIRING RESOLUTION IN ORDER TO APPRAISE FOREST ECOSYSTEM REPSONSES TO CLIMATE CHANGE INDUCED BY CO_2

ISSUES	KNOWNS	UNCERTAINTIES	UNKNOWNS
c. Chronic Age-Independent Mortality	Occurs when production is too slow to provide enough fixed carbon for metabolism, slowing growth, reducing resistance to stress	Quantification of "too slow" by species of tree	Will CO_2 experiments with seedlings apply to mature trees, reducing chronic age-independent mortality; future local and regional distribution, frequency of climate variance that slows growth
	Chronic insect predation on trees is a normal stress that vigorous trees survive	Will chronic insect attacks change because of changing climate variance, changing forest composition	Climate variance that controls insect population sizes, species composition; forest composition that controls same
	Air pollutant damage (gaseous, acidic precipitation) is an increasing stress from which vigorous trees previously survived	Future air pollutant levels; loss of tree vigor by species to future pollutant levels	Future combined effect of unknown air pollutant levels, climate extremes, insect, pathogen predation, and CO_2 effects on forest growth
d. Plant Succession	Rates, outcomes of succession under current constraints by climate variance, seed sources, disturbance frequencies, CO_2 concentrations	Will rates slow because of stress of possible continuous climate change; presence, intensity of forest-dieback and recovery	Will CO_2 enhance rates by relieving stress; future local and regional distribution of climate constraints (variance); future disturbance by wind, fire, flood
e. Plant Migration	Trees migrated 100-400m/y in the past 10,000-15,000 years	Future migration rates on a land-use dissected landscape, survival of seedlings of species ill-adapted to new conditions	Availability of seed sources with time; availability of empty niches; tree planting

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The primary focus of this section has been to evaluate what is known about the potential long-term response of plant abundances and range limits to large-scale climate change. Needed steps to reduce uncertainty and obtain accurate predictions of future vegetation change are also outlined. No accurate predictions can be made at this time, although there seems to be a weak consensus that vegetation change will be greater at high latitudes than at lower latitudes. Coastal vegetation is likely to be affected by an anticipated sea-level rise of approximately 1 meter (National Research Council, 1984). Uncertainty about the response of other vegetation to CO_2-induced change is compounded by the even greater uncertainty that surrounds the possible effects of climate forcing on short-term plant growth and the possible direct effects of CO_2 on the growth and the competitive balance of vegetation (Table II-1). For example, the actual shapes of ecological response functions could change with increasing concentrations of atmospheric trace gases. Considerable research remains to be done on all aspects of the vegetation-climate issue before accurate predictions can be made.

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III. EFFECTS ON AGRICULTURE

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A. Findings

1. Climate has had a significant impact on farm productivity and geographic distribution of crops. Examples include the 1983 drought, which contributed to a near 30 percent reduction in corn yields in the U.S., the persistent Great Plains drought between 1932 and 1937, which contributed to nearly 200,000 farm bankruptcies, and the climate shift of the Little Ice Age (1500-1800), which led to the abandonment of agricultural settlements in Scotland and Norway.

2. World agriculture is likely to undergo significant shifts if trace-gas-induced climate warming in the range of 1.5° to 4.5°C occurs over the next 50-100 years. Climate effects on agriculture will extend from local to regional and international levels. However, modern agriculture is very dynamic and is constantly responding to changes in production, marketing, and government programs.

3. The main effects likely to occur at the field level will be physical impacts of changes in thermal regimes, water conditions, and pest infestations. High temperatures have caused direct damage to crops such as wheat and corn; moisture stress, often associated with elevated temperatures, is harmful to corn, soybean, and wheat during flowering, and grain fill and increased pest infestation are often associated with higher, more favorable temperatures.

4. Even relatively small increases in the mean temperature can increase the probability of harmful effects in some regions. Analysis of historical data has shown that an increase of 1.7°C (3°F) in mean temperature for a city like Des Moines increases by about a factor of three the likelihood of a five-consecutive-day maximum temperature of at least 35°C (95°F). In regions where crops are grown close to their maximum tolerance limits, changes in extreme temperature events may have significant harmful effects on crop growth and yield.

5. Limited experiments using climate scenarios and agricultural productivity models have demonstrated the sensitivity of agricultural systems to climate change. Future farm yields are likely to be affected by climate because of changes in the length of growing season, heating units, extreme winter temperatures, precipitation, and evaporative demand. In addition, experiments

show that total productivity is a function of the availability of land, the location of soil and water resources, the ability of farmers to shift to different crops, and agricultural trade regulations.

6. The transition costs associated with adjusting to global climate change are not easily calculated, but are likely to be substantial. Accommodating to climate change may require shifting to new lands and crops, creating support services and industries, improving and relocating irrigation systems, developing new soil management and pest control programs, and breeding and introducing new heat- or drought-tolerant species. The consequences of these decisions on the total quantity, quality, and cost of food are difficult to predict.

7. Current projections of the effects of climate change on agriculture are limited because of uncertainties in global climate models' prediction of local temperature and precipitation patterns and because of the need for improved research studies using integrated modeling approaches.

B. INTRODUCTION

1. Importance of Agriculture

Recent famine in Africa and decline in U.S. trade shares for many commodities demonstrate the importance of agriculture both worldwide and in the national economy. Agricultural products must provide sustenance for the world's growing population, now estimated at 5 billion. Agriculture is also a critical American industry, contributing export products for the nation's trade balance.

Both production and consumption of grain have grown steadily worldwide since 1960, although fluctuations in production have occurred due to variations in climate and socioeconomic factors (Figure III-1a). Despite adequate world food supplies, production and distribution in Africa have deteriorated in the 1980's because of drought, low grain stocks, economic difficulties and lack of support systems. These problems have taken place within the context of normal climatic variability.

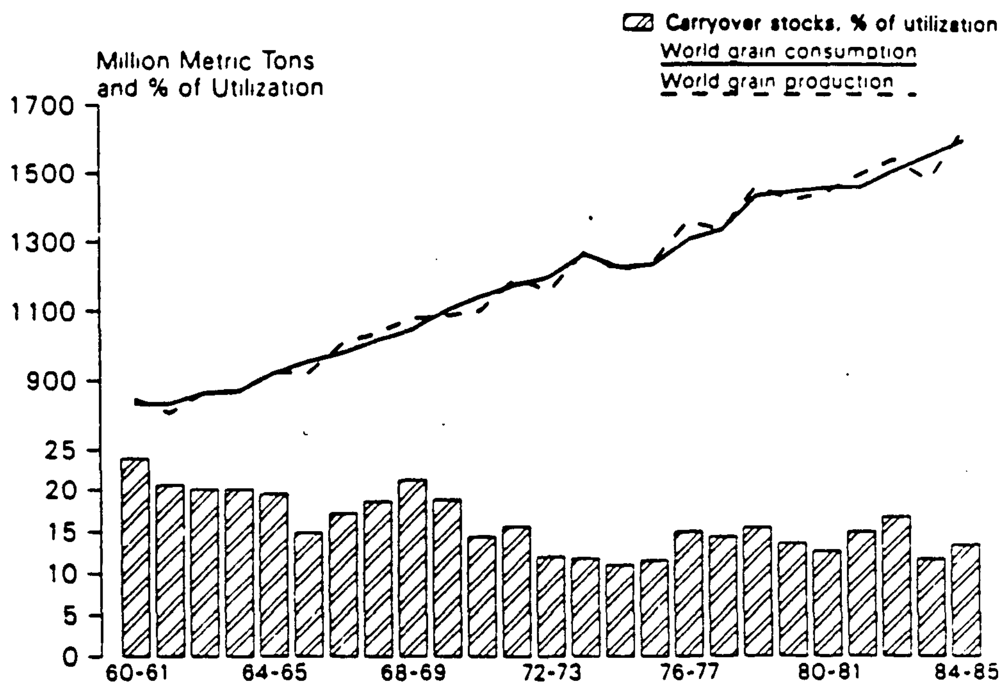
Total U.S. agricultural exports were valued at $38 billion for the 1983-1984 fiscal year, down from a peak of $42.6 billion in 1980-81 (Figure III-2). Grains and oilseeds account for approximately two-thirds of these agricultural exports in recent years. Although technological advances such as irrigation systems have reduced the dependence of crop yields on the natural environment, there is still a major response of yield to climate.

Parry (1986) provides several examples of the impact of previous climate fluctuations on agriculture. For example, midsummer 1983 saw a pronounced drought in the U.S. Corn Belt and the Southeastern United States. U.S. corn yields fell by about a third, from over 7,000 kg/ha to about 5,000 kg/ha. In the same year, however, the Payment in Kind Program (PIK) had encouraged large numbers of farmers not to plant corn (as part of an effort by the USDA to reduce the national grain surplus). As a result, the U.S. area planted to corn also fell by about a third, from 30 to 21 million ha. The combined effect of decreased yield and reduced area was a fall in U.S. corn production by almost one-half (from 210 million metric tons (mmt) in 1982 to 110 mmt in 1983). The effects were felt not only nationally, but also globally because U.S. corn accounts for about one-eighth of the world's total market cereal production. In 1983, world total grain production fell by 3%, harvested area by 1.4%, and yield by 2%, these reductions being almost fully accounted for by the U.S. figures alone.

An example of a prolonged climate event with cumulative impacts occurred in the Great Plains between 1932 and 1937. A persistent drought helped bring about 200,000 farm bankruptcies or involuntary transfers and the migration of more than 300,000 people from the region. If the same weather were to occur today, assuming 1975 technology and a 1976 crop area, the impact would still be considerable. For a recurrence of the worst weather-year, 1936, simulated wheat production for the region shows a drop of 25%, reducing national wheat production by about 15% (assuming average production elsewhere in the U.S.). The cumulative effect of a prolonged drought in the Great Plains could be

FIGURE III-1

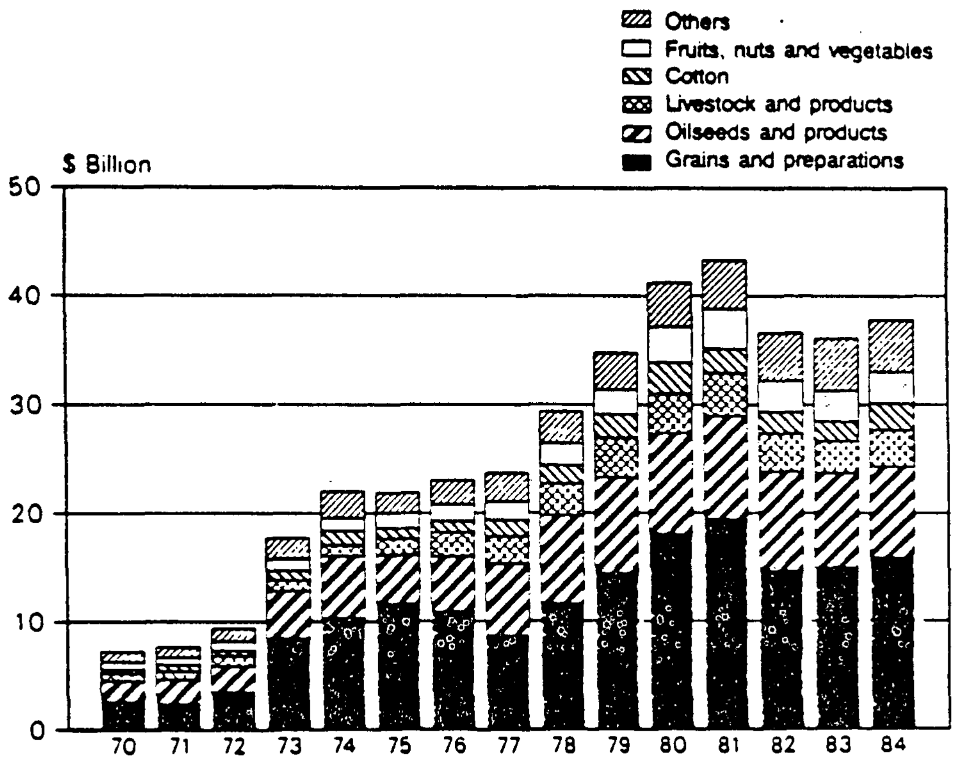
World Grain Production and Consumption



Source: U.S. Department of Agriculture, Foreign Agricultural Service, *Foreign Agriculture Circular, Grains*, FG 7-85 (Washington, D.C.), May 1985 and various other issues.

FIGURE III-2

U.S. Agricultural Exports



Source: U.S. Department of Agriculture, Economic Research Service, *Foreign Agricultural Trade of the United States* (Washington, D.C.), January-February 1985 and various other issues. Livestock excluding poultry and dairy products.

substantial: yearly yields simulated for the weather over the period 1932-1940 average about 9% to 14% below normal and amount to a cumulative loss over the decade equal to about a full year's production in the Great Plains (Warrick, 1984).

A final example of the importance of climate to agriculture can be found in the experience of western Europe during the Little Ice Age (1500-1800 AD). During that time, mean annual temperatures were about 1.5°C below the present norm and also of the preceding warm epoch of 800-1200 AD. At the nadir of this cold episode the accumulated temperature of the growing season in southern Scotland was 10% less than at present (Parry, 1978). There was a permanent snowfield in the Scottish highlands, where icebergs were reported to have drifted ashore carrying polar bears from the Arctic (Lamb, 1982). Widespread desertion occurred at the more marginal upland settlements in Scotland, and in Norway about half of the farms were abandoned in the late Middle Ages (Parry, 1978). In Iceland the cultivation of cereal grains died out before 1600AD. The period was clearly one of considerable difficulty for those farming near the northern limit of agriculture. Even under these unusual climatic conditions, however, there existed a range of adjustments which farmers could employ to respond and survive. Abandoning settlements and moving southward was one form of response.

Future changes in climate will affect agriculture because light, water, and temperature regimes are important forces that govern plant growth and reproduction. As climatic factors change, a cascade of effects will occur throughout the agricultural system, general economy, and society (Figure III-3). Physical effects of climate change on the field level, such as changes in thermal regimes, water conditions, levels of pest infestations, and, most important, yields, may lead to changes in farm management decisions based on altered risk assessments. Consequences of the combined management decisions of many farmers could result in changes in farming systems, land use, and food quality. Ultimately, impacts of climate change on agriculture may reverberate throughout the global food economy and thus through society as a whole.

2. Description of this Study

This section will address three important questions concerning climate change and agriculture:

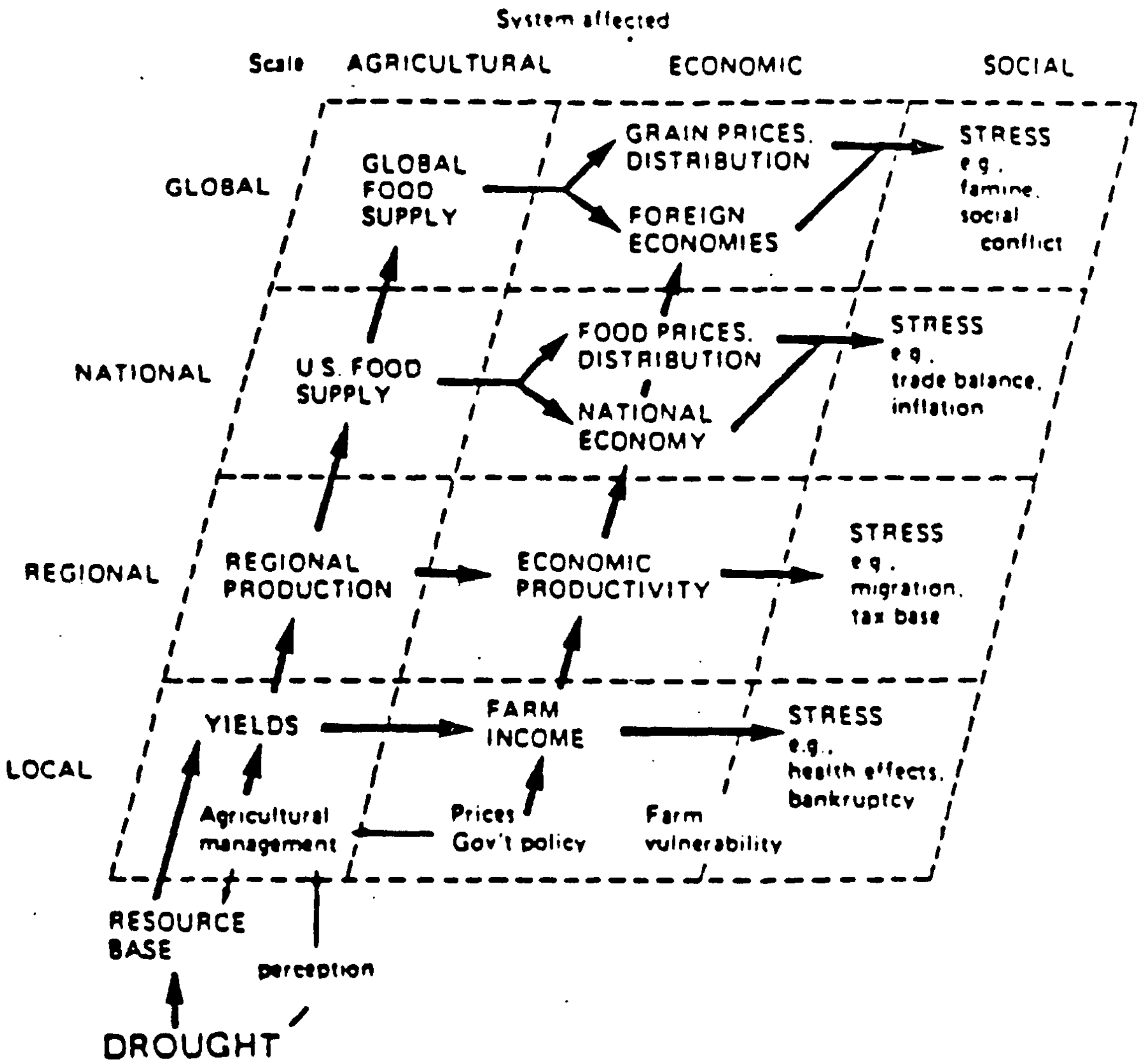
1. What are the major physical effects of climate change on agricultural crops and what are the potential consequences of these effects?

2. What methods are available and most appropriate for assessing the impact of climate on agriculture?

3. What are the future directions for research on impacts of climate change on agriculture?

FIGURE III-3

The Hypothetical Pathways of Drought Impacts on Society



Source: Warrick and Bowden, 1981.

Current concern about climate change is due to the observed increase of atmospheric trace gases, particularly of CO_2 (Keeling et al., 1982). Since CO_2 and the other trace gases absorb infrared radiation from the earth's surface, global warming and other climatic effects have been predicted with general circulation models (GCMs) (see Figure III-4) (Manabe and Stouffer, 1980; Hansen et al., 1981; Washington and Meehl, 1984). At the same time, CO_2 is a necessary component of photosynthesis and affects stomatal opening with possible lowering of the rate of transpiration; therefore it has direct physiological effects on agricultural crops (Lemon, 1983). Research on the direct physiological effects of increased CO_2 on vegetation is described in Strain and Cure (1985).

This review concentrates on the climatic rather than on the physiological effects of increased trace gases. However, it is difficult to separate these effects, since in some cases they are interactive; for example, transpiration rate is related to both temperature and CO_2 level. Some studies have examined both climatic and physiological effects simultaneously; more studies of this kind should help to clarify their interactions. This review is also limited to the effects of climate change as projected by GCM studies of increased atmospheric trace gases. All GCM studies predict warmer surface temperatures; some predict lower growing season soil moisture. However, climate change effects on the hydrologic cycle are not well understood due to the lack of ocean dynamics and physically based ground hydrology in GCMs. Regional precipitation estimates must be viewed with caution. Finally, research reported in this paper concentrates on the effects of climate change on crops rather than on animal or forage production. For a review of animal and forage production see Decker et al. (1986).

C. POTENTIAL EFFECTS OF CLIMATE CHANGE ON CROPS

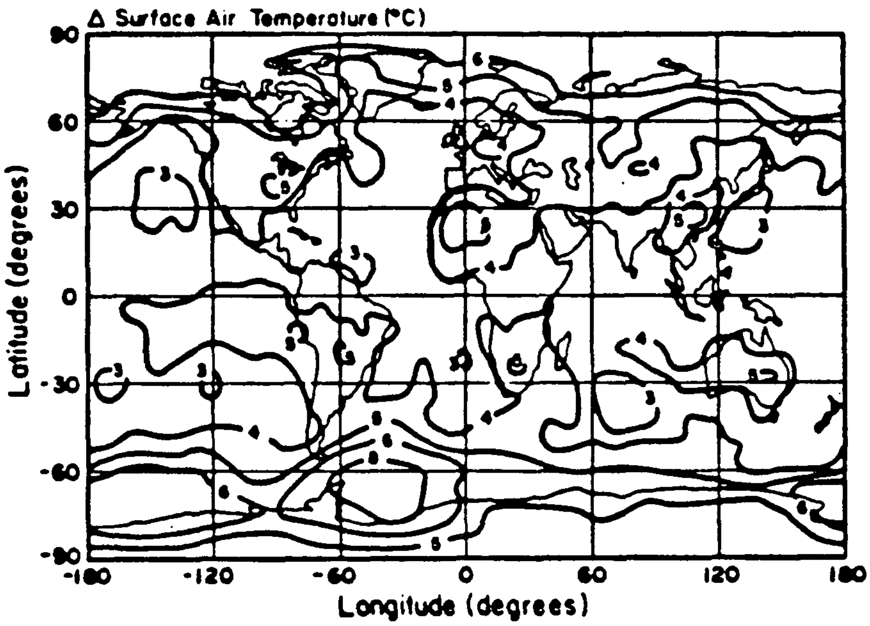
The major effects of climate change on physical aspects of crop growth are changes in (1) thermal regimes, (2) water conditions, and (3) pest infestations. These are all important determinants of yield. Other aspects of agriculture that may be affected by climate change are soil fertility, erosion, and plant breeding. Potential consequences of these physical effects are shifts in cropping patterns with ensuing changes in land use, environmental impacts and food quality. Eventually, economic effects may extend from the farm all the way to global food trade.

1. Thermal Regimes

One consequence of trace-gas-induced climate change important to crops is a lengthening of the growing season, usually defined as the period from the last frost in the spring to the first frost in the fall. Longer growing seasons may allow earlier planting dates, earlier maturity and harvesting, and multiple cropping (growing more than one crop in a season). Another consequence of warmer climate for crops is an accelerated accumulation of thermal units. By summing temperatures over time and relating the summations to crop phenology, agronomists have developed indices that quantify the thermal requirements for various crops (Newman, 1980). These thermal units, often called growing degree days (GDDs), are based on daily or monthly minimum

FIGURE III-4

Geographical Distribution of Annual Mean Surface Air Warming
for Doubled Atmospheric CO2 in the GISS GCM



Source: Hansen et al., 1984.

and maximum temperatures. Newman (1980), Blasing and Solomon (1984), and Rosenzweig (1985) all used GDDs in their analyses of potential climatically-induced changes in crop locations and found that increased accumulation of GDDs would contribute to geographical shifts in U.S. corn and Canadian wheat belts (Figure III-5).

High temperatures can cause damage to crops. Ramirez and Bauer (1973) found that the number of days that temperatures exceeded 32°C has a significant effect on final yield of wheat. Daily maximum temperatures above 32.2°C have significant negative effects on corn yields (Thompson, 1975) and the number of days with maximum temperatures above 37.8°C has been related to decreased corn yields (McQuigg, 1981). Developmental stage is related to vulnerability of crops to damage caused by high temperatures. For example, extreme high temperatures are particularly damaging to wheat at the time of grain filling: high temperatures with daily maxima of 30°C or greater can terminate grain filling (Evans et al., 1975). Results from GCMs can provide results that estimate the changes in number of days above, for example, 32.2°C for a given location (Hansen, 1986) and hence can be used to develop insights about the impacts on wheat-growing regions and crop yields. These can then be related to decreases in crop yields. Heat-tolerant varieties of major crops may become an important plant-breeding objective.

2. Water Conditions

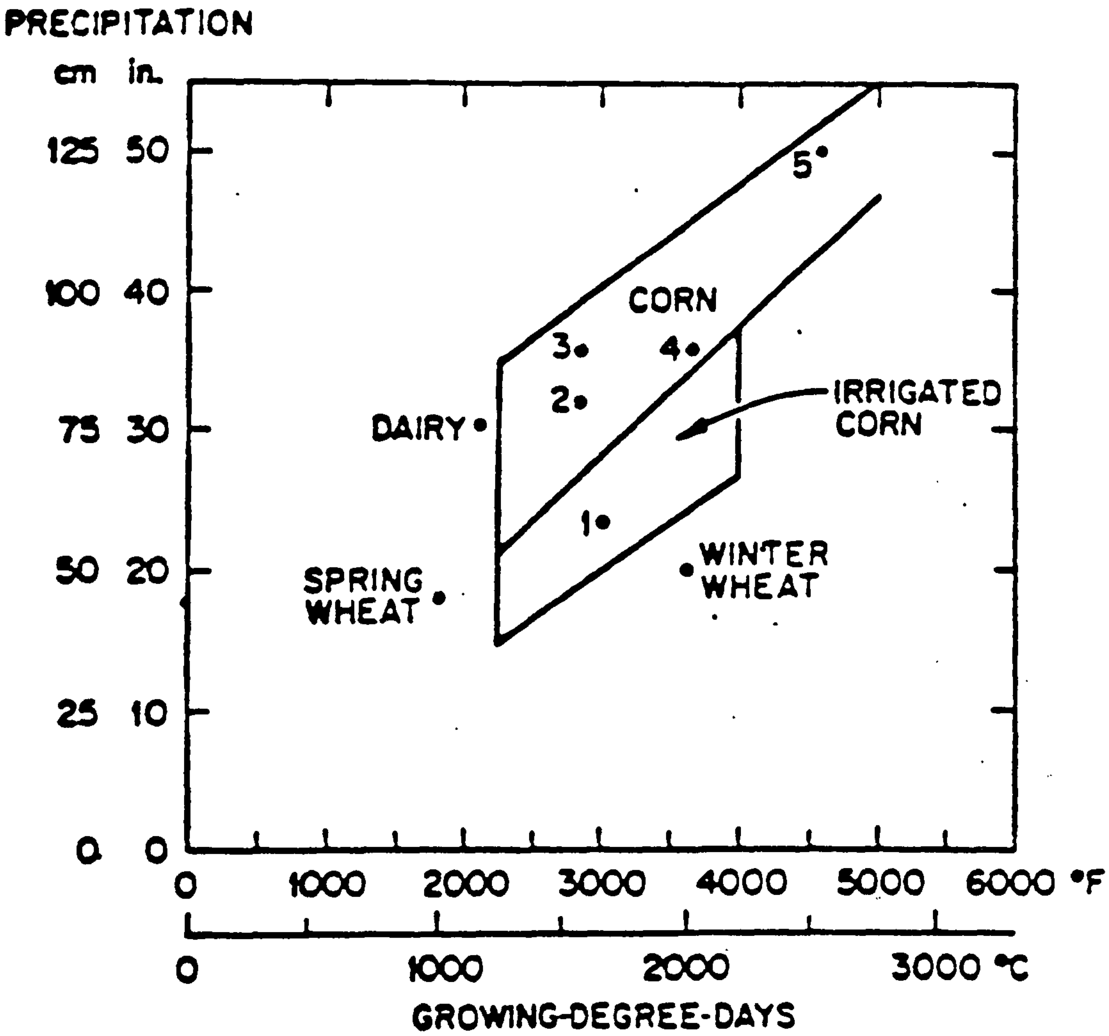
Summer dryness and decreased soil moisture in the interiors of continents have been predicted from some climate models (Manabe et al., 1981; Manabe and Wetherald, 1986); however, all climate models do not show these effects (Rind, 1986). But even if summer dryness in continental areas is not ubiquitous, shifts in rainfall patterns are predicted by GCMs for some areas. Changes in water regimes for agriculture in any given region may occur because of changes in total and/or seasonal precipitation, seasonal distribution of precipitation, and interannual variability. In general, global precipitation, especially at high latitudes, is expected to increase due to the capacity of warmer air to hold more water vapor. However, the same increase in capacity will be responsible for an increase in evaporation and this suggests that drier conditions (in terms of soil moisture) should accompany climatic warming even if rainfall patterns are unaffected.

If dry periods occur during critical development stages of a crop, yields may decrease (Figure III-6). For example, moisture stress during flowering (pollination) and grain fill are harmful to corn, soybeans, wheat and sorghum (Decker et al., 1986). Farmers may respond to shifts in rainfall regimes by changing irrigation schedules or by utilizing soil moisture conservation techniques such as minimum- or no-tillage, and mulches. More conservative irrigation techniques, such as trickle or drip systems, would probably increase in drier summer conditions (see Withers and Vipond, 1980). Breeding crop varieties with greater drought-tolerance may become important.

Farmers may respond to summer dry periods simply by increasing demand for irrigation water. Studies such as one by Callaway and Decker (reported in Decker et al., 1986) have simulated irrigation demand using prescriptive

FIGURE III-5

Heat and Moisture in the North American Corn Belt

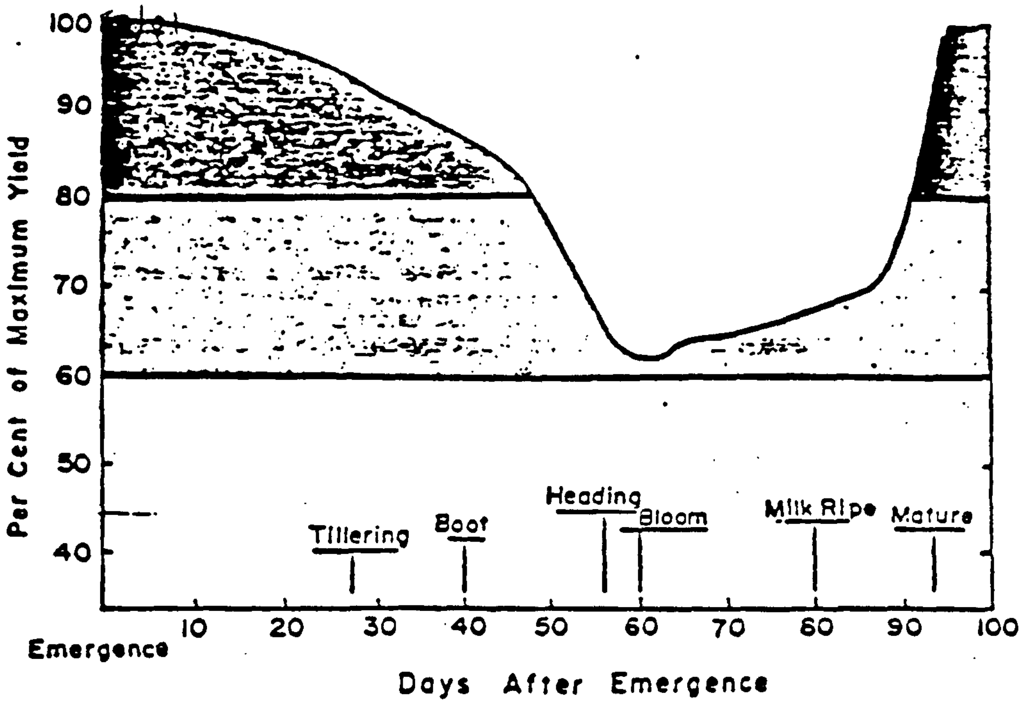


Heat and moisture characteristics of the North American corn belt. Numbers 1-5 correspond to geographical locations in or near the corn belt. Dots outside the lines correspond to central Wisconsin (dairy), central North Dakota (spring wheat), and west-central Kansas (winter wheat).

Source: Blasing and Solomon, 1984.

FIGURE III-6

Effect of Water Stress at Various Growth Stages on Grain Yield Reduction in Wheat



Source: Ramirez et al., 1975.

climate scenarios. Where water supplies are already diminishing, extra demand could require some land to be removed from irrigation. For example, in the region supplied with water by the Ogallala aquifer, it may become uneconomical to irrigate cropland as energy costs and well depths increase, even without climatic warming (High Plains Associates, 1982). Studies that examine potential irrigation needs for climate change should take availability of water resources into account (Glantz and Ausubel, 1984).

If rainfall patterns change and irrigated agriculture moves to new locations in response, previous investments may be lost and new investments needed for the new locations. The economic costs of shifting the location of irrigated agriculture could be considerable. Construction of irrigation systems consisting of reservoirs, ditches, pumps, sprinklers, and wells requires extensive capital investment (estimated by Postel (1986) to be between $1500 and $5000 per hectare).

3. Pest Infestations -- Insects, Diseases, and Weeds

In a warmer climate, as predicted for increased atmospheric trace gases, insect pests may increase due to higher, more favorable temperatures (see Hatfield and Thomason, 1982). Longer growing seasons may increase the number of insect reproductive cycles during crop growth, and warmer winter temperatures may allow over-wintering of larvae, now limited by cold, thereby increasing infestations. Ranges of insects could extend to higher latitudes, particularly since warming is predicted to be greater in those regions. Altered atmospheric circulation patterns may affect the spread of wind-dispersed disease pathogens. Finally, shifts in timing of development stages may change plant/pest interactions since crops, insects, diseases, and weeds may respond differently and at different rates to changing climate (Decker et al., 1986).

Since agronomists, entomologists, plant pathologists, and weed specialists are used to responding to changing pest situations, their adaptations to changing climate will most probably be extensions of their current techniques: climate and pest monitoring, crop breeding for new resistances, changes in planting dates, continued study of pest behavior, and improving integrated pest management techniques (Hatfield and Thomason, 1982).

4. Soil Fertility and Erosion

It is difficult to estimate the effects of trace-gas-induced climate change on soil fertility and erosion. Warmer temperatures could alter the microbial decomposition of organic matter thereby adversely affecting soil fertility. Increases in root biomass due to increased photosynthetic activity might offset potential decreases in fertility. Cycling of nutrients may be accelerated and nitrogen fixation increased. Biomass accumulation and decomposition of organic matter might be decreased if summers are drier (as suggested by Manabe and Wetherald, 1986). Fertilizer applications would be likely to change in response to these effects.

Summer dryness might also increase both water and wind erosion due to reduced vegetation cover and drier soil particles. This could generate a "Dust Bowl" effect. In areas where soil moisture is reduced, minimum- or no-tillage management systems can reduce these types of erosion.

5. Consequences to Agricultural Systems

a. Cropping Patterns

Crop regions will begin to shift as soon as comparative economic advantage shifts. Eventually, as climate zones change, environmental requirements for different crops may not be fulfilled and substitutions will become necessary. Support services and industries will need to be created, as well as new markets in new locations. The costs of changing farming systems can thus be considerable, especially when land-use planning and environmental impacts are taken into account. Another effect of climate change may be the loss of agricultural land due to sea level rise, if expansion of the oceans and melting of high-latitude ice occurs as predicted.

If milder winters and longer growing seasons occur, agriculture may extend north into sensitive areas such as northern woodland and forest ecosystems. This would introduce agricultural chemicals into the land and water systems and expose soils to erosion. Many of the soils in these areas are relatively infertile and require careful management if they are to be used for agriculture (Furuseth and Pierce, 1982). Substantial investment would be needed to prepare these soils for agriculture and erosivity may be higher.

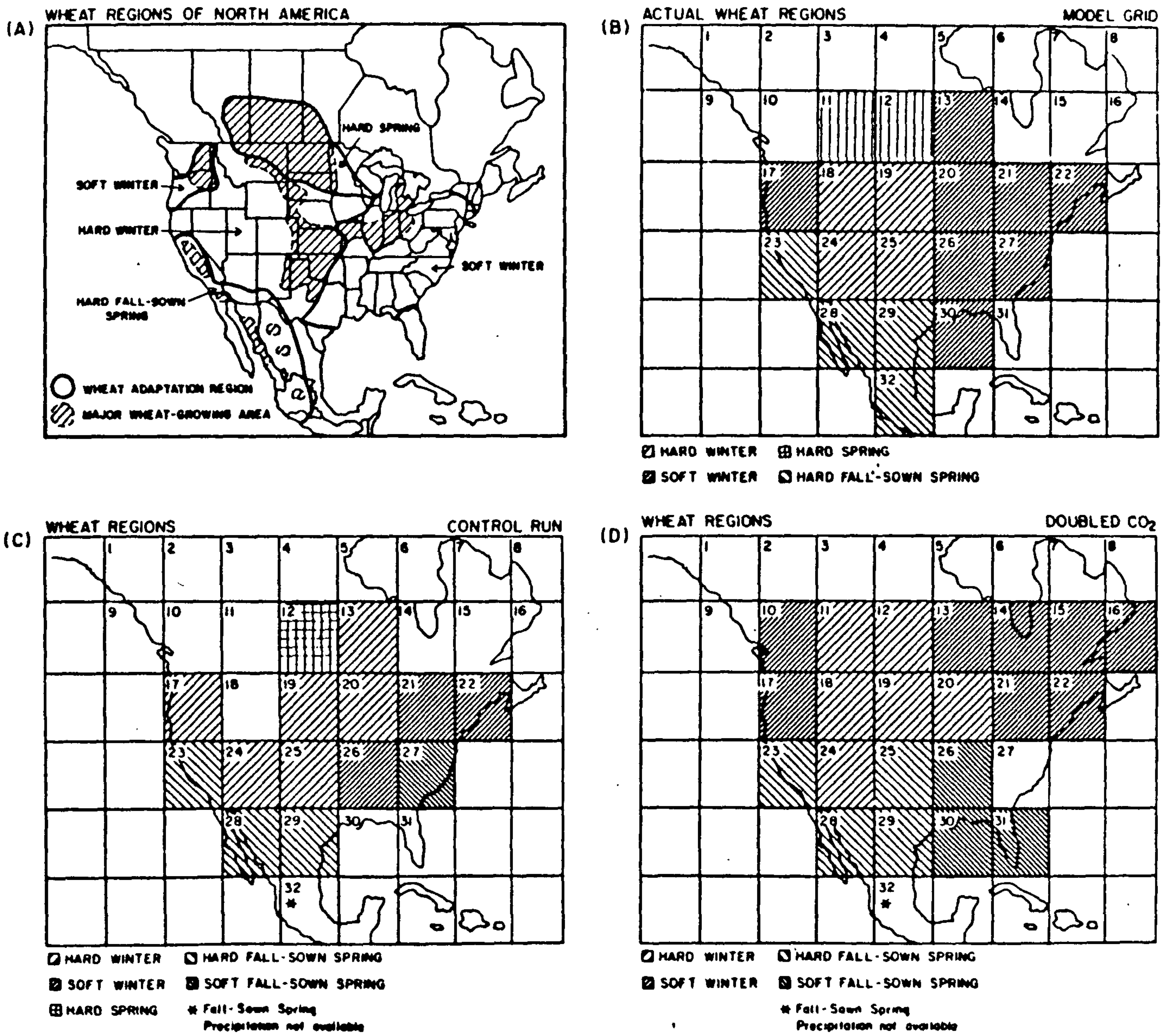
Another aspect of shifts in cropping patterns may be changes in food and grain quality. For example, several studies have shown that winter wheat may replace spring wheat in northern areas (Figure III-7) (Stewart, 1986 and Rosenzweig, 1985). However, the protein content of winter wheat is not quite as high as that of spring wheat (Martin et al., 1976). In other areas, wheat types grown for animal consumption may replace wheat grown for human consumption.

b. Plant Breeding

Plant breeding for the predicted climate change will most likely be focused on development of heat- and drought-tolerant varieties of major crops. In general, the agricultural research and plant-breeding communities are confident about their ability to respond to the climate changes predicted by GCMs. If the change is gradual, this attitude may be justified, since new varieties of major crops (corn, soybean, wheat, and sorghum) can be developed in 10 years or less (Decker et al., 1986). On the other hand, recent research reports show projected warming may begin to be observable in the next decade and may be quite rapid (Hansen, 1986). Since the projected temperature trends are all in one direction, new varieties may always be about a decade behind in levels of heat tolerance. Genetic resources may be strained if mean surface temperature changes reach or exceed the high values (i.e., 4.5°C) predicted by GCMs for doubled CO_2.

FIGURE III-7

Wheat Regions of North America



(A) Major wheat-growing areas of North America. Source: U.S. Wheat Associates and Foreign Agricultural Service, USDA; (B) Actual wheat-growing regions of North America on the GISS GCM grid; (C) Simulated North American wheat regions using the GISS GCM control run; (D) Simulated wheat regions using the GISS GCM doubled CO2 run.

Source: Rosenzweig, 1985.

D. ASSESSING CLIMATE IMPACTS ON AGRICULTURE: METHODS AND RECENT RESULTS

The variety of research methods used to study the effects of climate change on agriculture includes:

- Climate scenarios are developed to guide both modeling and chamber studies in the specification of temperature and water regimes. These scenarios may be specified either as simple prescriptive changes (e.g., +2°C in July) or from historical ranges based on meteorological observations, or may be derived from global climate modeling results.

- Controlled atmosphere studies (conducted in phytotrons, greenhouses, and field chambers) are used to determine the direct physical consequences of specified climatic regimes, often combined with increased atmospheric $CO2$, on agricultural crops.

- Statistical regression models are used to relate historical crop yields in a specific location to concurrent or antecedent climatic factors.

- Dynamic process crop growth models employ functional relationships of the transfer of mass and energy in crop canopies and soil and climatic factors to determine crop growth and yield.

- Probability analyses are used to estimate changes in extreme climatic events, such as drought or high temperature, and their effects on crop yield.

- Integrated agricultural and economic models combine results from all of the types of studies above to develop economic estimates of the cascading effects of climate change throughout economic sectors of society.

1. Climate Scenarios

Climate scenarios must be developed for chamber studies, statistical regression analyses, and for climate-driven dynamic crop growth models. These may be simple prescriptive changes such as a 2°C increase in July temperatures or more complex sets of changes derived from recorded or modeled climate.

a. Simple Prescriptive Changes

The simplest approach to scenario development is the application of prescriptive changes (such as a 2°C increase in temperature or a 10% decrease in precipitation over the whole or part of a year) to observed climate. Tests with these simple changes are in the nature of sensitivity studies. Waggoner

(1983) used this approach to study yields for the major cropping regions of the United States using regression and crop growth models. For a 1°C warming and a 10% decrease in rain, the decrease in yields ranged from 0.04 to 0.18 T/ha, a decrease of between 2% and 12%.

Newman (1980) used growing season thermal units to measure the sensitivity of the corn belt to ±1°C daily temperature changes. He found that the corn belt would shift 175 km per degree centigrade in a SSW or NNE direction. Newman did not consider precipitation changes per se, but did include the impact of a ±5°C temperature change on potential evapotranspiration in the simulation.

b. Historical Analogs

Studies of historical periods are useful for providing insight into the responses of farmers and farming systems to prolonged climatic extremes such as the Dust Bowl Years (1930's) in the Southern Great Plains (see Wigley et al., 1981). The use of specific historical analog scenarios for modeling studies is based on the assumption that patterns of climate warmings are similar regardless of atmospheric forcing mechanism. Manabe and Wetherald (1980) have shown that climate model variables reacted similarly to two different types of forcing, increased solar constant and higher atmospheric CO_2. This argument has been used to justify the development of scenarios from 20th century records (Lough et al., 1983).

Lough et al. (1983) constructed climate scenarios for the Northern Hemisphere based on the instrumental observations of the warmest five-year and twenty-year periods in this century. The warmest period occurred from 1934 to 1953 (Figure III-8). The effects of these climate scenarios on crop yields in England and Wales were calculated by means of regression models that were developed from a principal components regression technique. Results showed a decrease in yield for most crops due to warmer summers, drier springs, and wetter autumns.

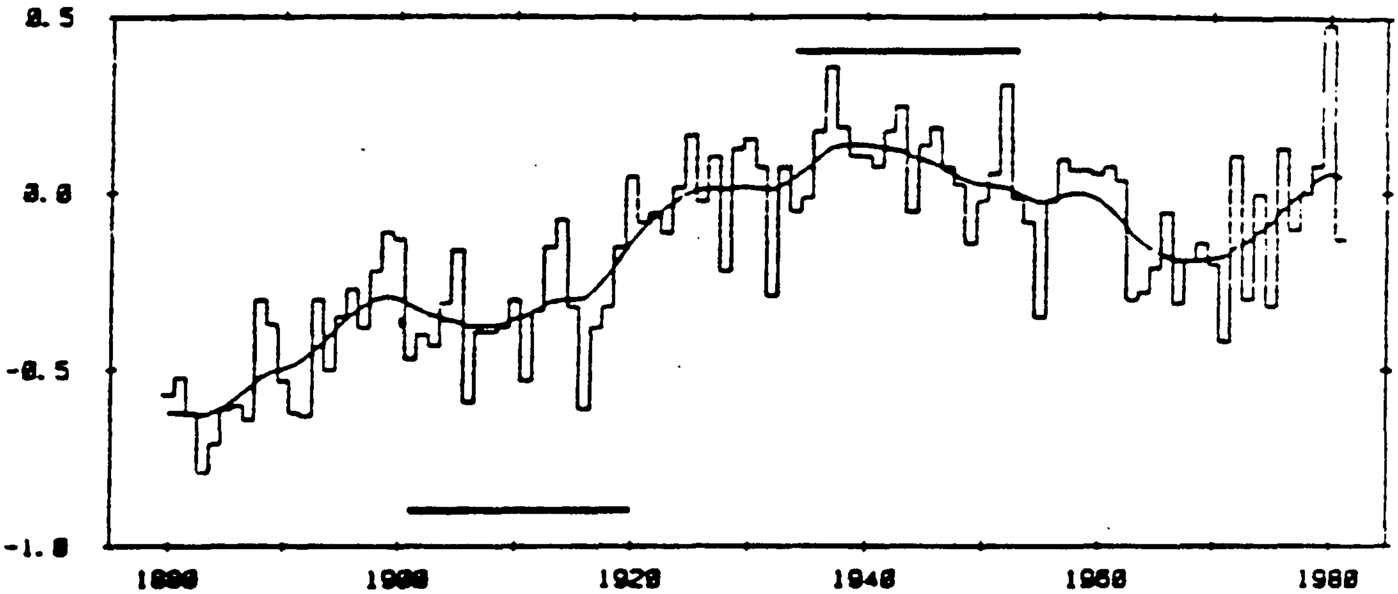
The climate forcing argument used to justify the analog approach may not hold for previous 20th century warm periods, since it is not obvious that the solar constant has been higher, and increased CO_2 effects have probably not yet been evident during this century. Also, the temperature rise of the warmest period in the 20th century is only 0.4°C (warm minus cold temperature change for the Northern Hemisphere) compared to the predicted rise for doubled CO_2 which is 1.5°-4.5°C (doubled CO_2 run minus control run for global mean surface temperature) (National Research Council, 1982). Therefore, neither the forcing mechanism nor the magnitude of the 20th century warm period analogs appear to be appropriate for climate change studies due to increased trace gas concentrations.

c. Scenarios Developed from Climate Models

GCMs simulate climate by solving the fundamental equations for conservation of mass, momentum, energy and water. Output from GCM experiments with specified climate forcing mechanisms (e.g., doubled or quadrupled

FIGURE III-8

Northern Hemisphere Temperature Variations



Northern Hemisphere mean surface air temperature variations (°C) showing the chosen warm and cool 20-year periods. The curve shows 20-year filtered values using a 15-term Gaussian filter padded at each end with the mean of the first or last seven values.

Source: Lough et al., 1983.

atmospheric CO_2 levels) have been used in agricultural impact studies. The advantages of this type of scenario are their internal consistency and global extent. Disadvantages are the present lack of realism of the GCMs at regional scales (particularly for precipitation) and their coarse spatial resolution. Even though GCMs reproduce global climate realistically, they are not yet reliable for regional scale studies. Gridbox sizes in various GCMs range from 330 km x 330 km (approximately 100,000 km^2) to 8° latitude x 10° longitude (about 600,000 km^2) at 45° latitude.

Another problem with most GCM scenarios is the use of a step change in the atmospheric CO_2 content. Results from these model experiments show the equilibrium response of climate to increased trace gases, whereas the nature of the transient climate should be the real concern. To date, only one GCM study has used gradually increasing trace gas levels (Figure III-9) (Hansen et al., 1986). Results show global warming of 1°C by the mid-1990's and of 2°C by 2020.

d. Studies with GCM Climate Scenarios

Output from GCMs has been used to study impacts of CO_2-induced climatic change on West European agriculture (Santer, 1985), potential shift in the U.S. corn belt (Blasing and Solomon, 1984), potential impacts on North American wheat-producing regions (Rosenzweig, 1985), yields of spring wheat in Saskatchewan, Canada (Stewart, 1986), and implications for Ontario's agriculture sector (Smit, 1986).

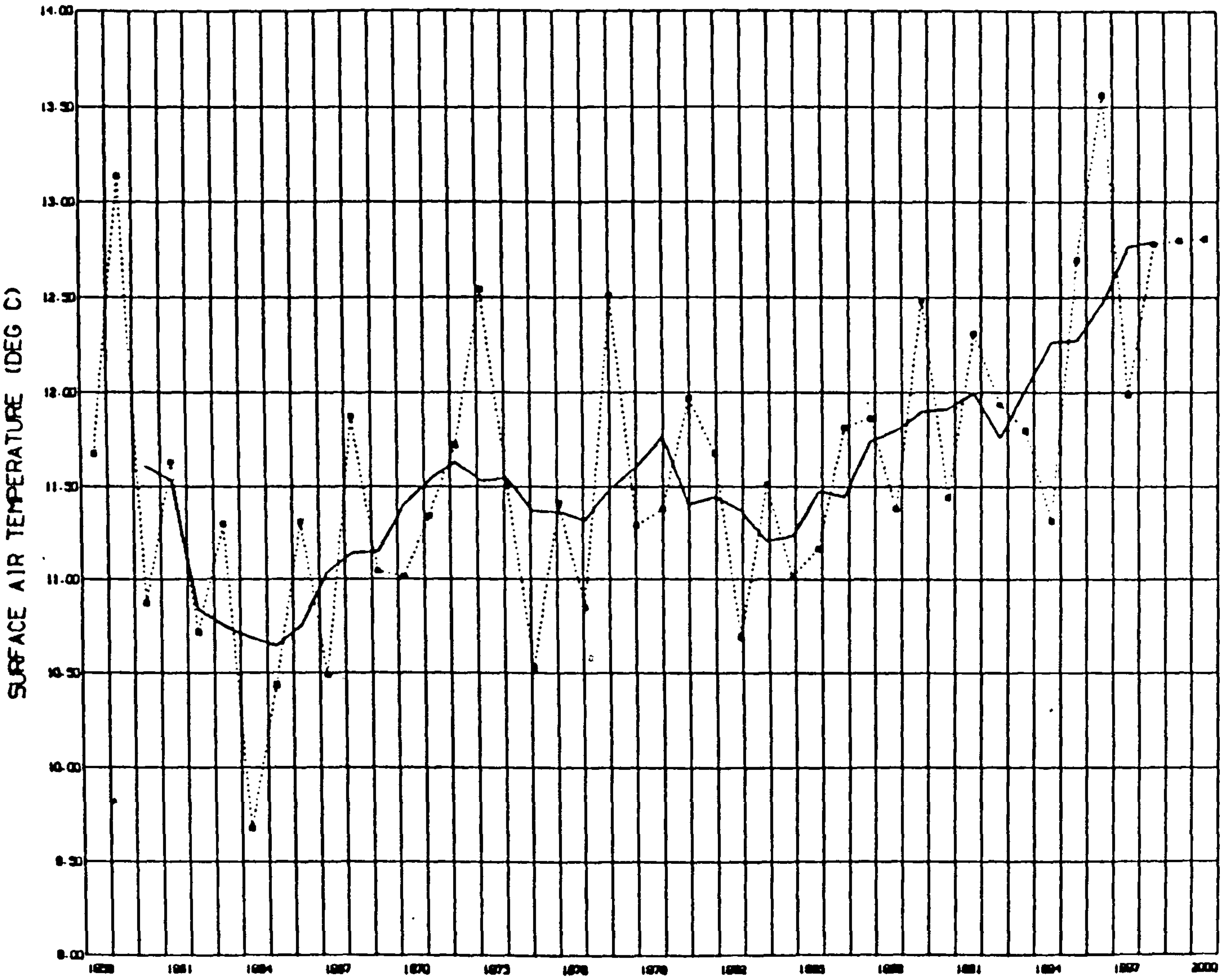
Santer (1985) examined assumptions and methodologies for study of climate change impact on agriculture. He used output from two GCMs, that of the Goddard Institute for Space Studies (GISS) and the British Meteorological Office (BMO), to run a linear regression model for winter wheat yield and a simple biomass production simulation model. The simulation model appeared to provide more physically realistic results than did the linear regression model for various European regions.

Blasing and Solomon (1984) mapped potential shifts in the corn belt using selected temperature and precipitation simulations obtained by halving values from a quadrupled CO_2 run of a climate model (Manabe and Stouffer, 1980; Manabe et al., 1981) in relation to thermal unit and precipitation requirements for corn. The study indicated that projected warmer and drier conditions favored the replacement of corn with other more adapted crops, such as winter wheat in the southwestern corn belt, and that regional climatic effects of the Great Lakes prevented the corn belt from extending appreciably northward.

In order to generate wheat regions for a potential CO_2-induced climate, Rosenzweig (1985) specified environmental requirements for growth of different wheat types in North America and compared them to temperature and precipitation results from the control and doubled CO_2 runs of the GISS GCM. Changes in modeled precipitation due to doubled CO_2 were applied to observed precipitation. In the simulation, areas of production increased in North America, particularly in Canada, due to increased growing degree units. Major

FIGURE III-9

Calculated Temperature Trends for the Southern Great Plains Gridbox for the Transient Run of the GISS GCM



Source: From experiment described in Hansen et al., 1986.

wheat regions in the U.S. could still support wheat production, although types of wheat grown changed in some locations. Wheat regions in Mexico were identified as vulnerable due to high temperature stress.

Stewart (1986) used GISS GCM results from a doubled CO_2 experiment to run a generalized crop growth model for Saskatchewan spring wheat by modifying the temperature and precipitation data in relation to the 1951-1980 normals. Without any direct effects of CO_2 (i.e., increased photosynthesis and water-use efficiency), modeled wheat production was reduced by 16-26%. Even with a 15% increase in photosynthetic capacity, wheat production was reduced (Figure III-10). An implication of these results is that mid-summer drought would be likely to cause farmers to shift to fall-sown crops, since the life cycle of winter wheat allows better utilization of fall and spring precipitation.

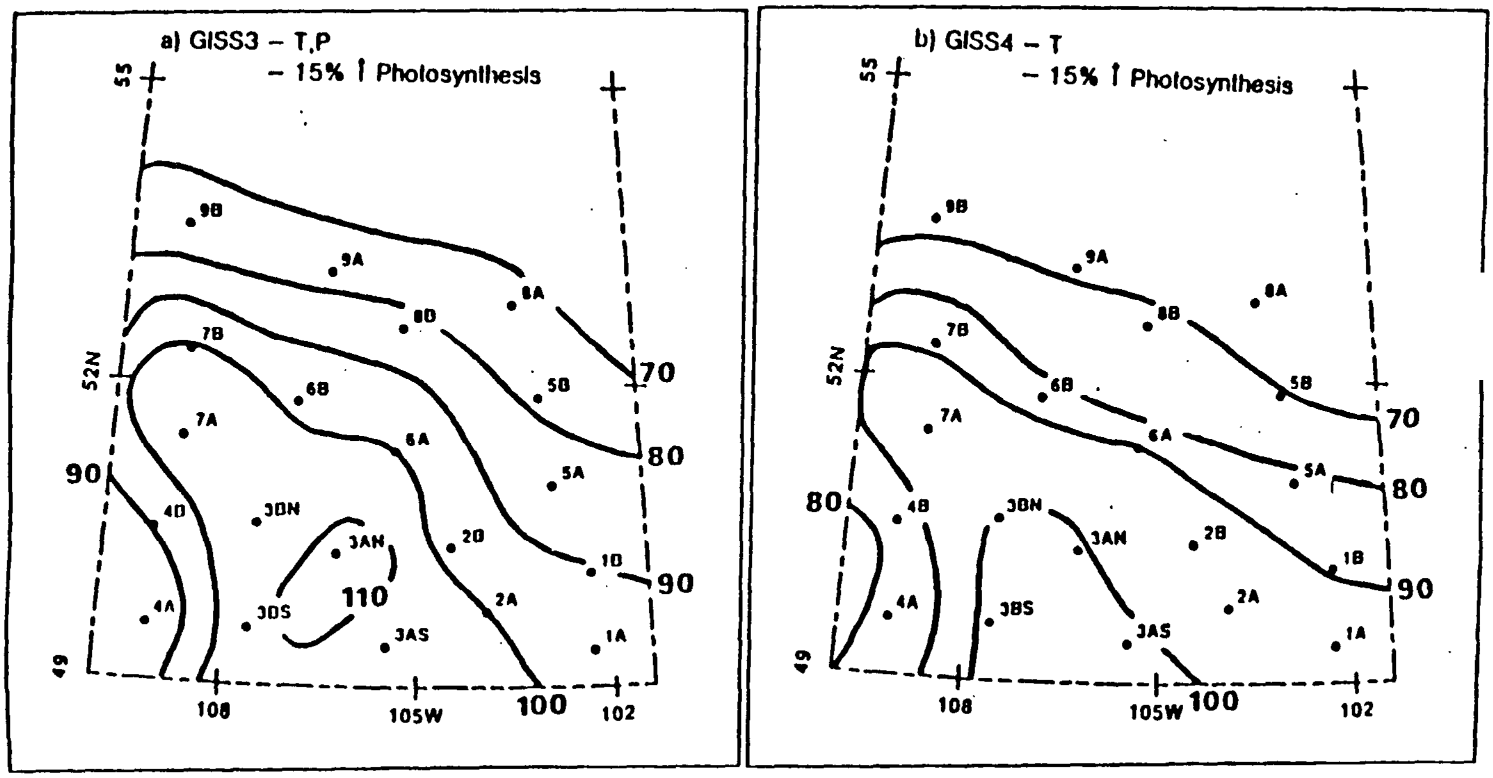
Smit (1986) used estimates of the potential impacts of a doubling in atmospheric concentration of CO_2 on monthly normals for mean temperature and total precipitation derived from a general circulation model developed by the Atmospheric Environment Service (AES), Environment Canada. These data were used to estimate agroclimatic resources (e.g., length of growing season, heat units, evapotranspiration) available for crop production in each of six regions in Ontario. Estimates of the current range in precipitation levels for each defined region in Ontario were derived using monthly precipitation levels recorded between 1951 and 1981. In the absence of information on the degree to which the equivalent of a doubled CO_2 environment might affect variability in annual levels of precipitation, it was assumed that the relative range in precipitation about the norm for the growing season would not change.

Smit's results suggest that risks to agricultural production in Ontario would increase substantially given the specified changes in climate, especially in those years with low precipitation levels. Changes in long-term normals would contribute to a modest decline in production potential (Table III-1), but these losses could be recouped in those years with higher than average precipitation during the growing season. The largest is associated with drier than average years. Relatively dry years currently impinge upon provincial opportunities for food production. Low levels of precipitation, combined with the estimated increases in long-term temperature normals, would impose severe constraints on crop production opportunities and could threaten the security of Ontario's food supply.

Smit's results demonstrate the complexity of potential impacts of climate change on regional agriculture. For example, in Northern Ontario the array of crops that could be grown under the altered climatic regime would be expanded to include corn, wheat, and soybean. Furthermore, yield for the forages and cereal grains that are currently grown in Northern Ontario would increase substantially. In drier years, production on lands with a lower tolerance to drought would be limited, but these losses would be countered by enhanced prospects on lands with relatively high moisture reserves. The opposite would be expected in years with above average levels of precipitation.

FIGURE III-10

Variation in Spring Wheat Yields (% of Normal) in Saskatchewan for Two Scenarios Derived from GISS GCM Doubled CO2 Results



Source: Stewart, 1986.

TABLE III-1

Ontario's Potential for Food Production Given Changes in Long-Term Climatic Normals (thousands of metric tons)

CROP	PRODUCTION POTENTIAL GIVEN: Current Norms (Scenario 1)	Future Norms (Scenario 2)
Grain Corn	7804	7485
Barley	1761	1689
Oats	1104	1059
Winter Wheat	1063	1019
Soybeans	1176	1127
Hay	8590	8238
Fodder Corn	11678	11200
Potatoes	614	589
Improved Pasture	7865	7543
Unimproved Pasture	550	528

Source: Adapted from Smit, 1986.

In the southern parts of Ontario, moisture stress associated with the longer and considerably warmer summers would impinge upon the production opportunities for most field crops, despite the longer growing season. The greatest impacts would occur on well-drained -- to excessively well-drained -- lands during the drier years.

2. Controlled Atmosphere Studies

Results from field experiment studies may relate the current range of variability in climatic factors to crop yield. When the effects of specific climate regimes are studied, controlled atmosphere experiments in phytotrons, greenhouses, or field chambers are conducted. These have often been used to combine the effects of climate and increased CO_2 on crop growth. However, these controlled atmosphere experiments rarely use climate regimes that are based on climate change projections.

Studies combining both controlled climatic factors (e.g., light, temperature, and/or moisture) and physiological effects of increased CO_2 have been done on corn (Goudriaan and de Ruiter, 1983), cotton (Mauney et al., 1978), potato (Collins, 1976), sorghum (Marc and Gifford, 1984), soybean (Sionit, 1983), and wheat (Chaudhuri et al., 1986, see Figure III-11).

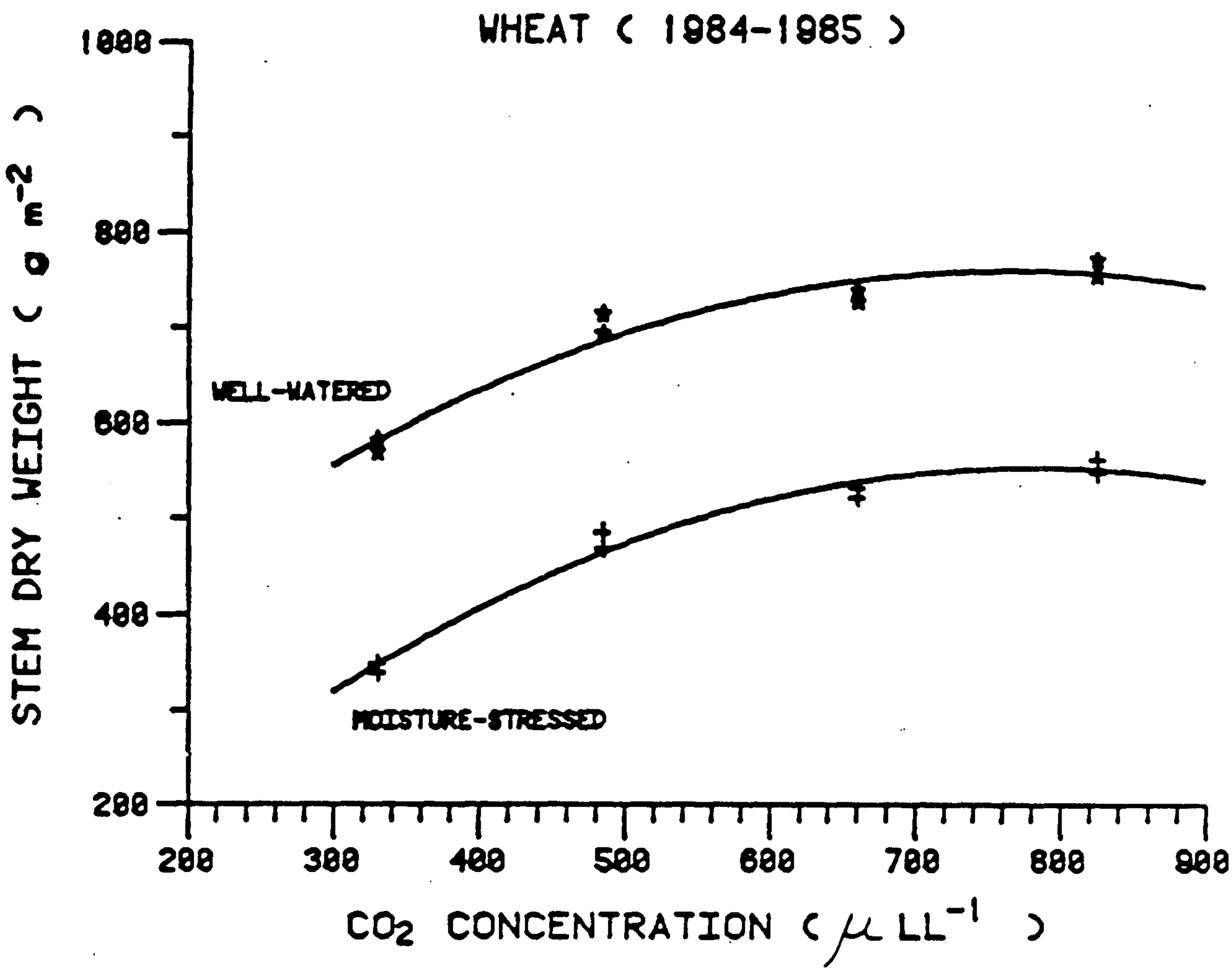
3. Statistical Regression Models

Multivariate regression models have been developed from the relationships between historical crop yields in a specific location and climatic variables. These relationships have been used to predict future yields under varying climatic scenarios. Among the many models of this type are those of Thompson for corn (1969a) and wheat (1969b) for parts of the central United States; Haigh (1977) for corn, soybean, and wheat for certain states in the mid-west; Baier (1973) and Williams (1975) for wheat in Canada; and Ramirez et al. (1975) for wheat in the Great Plains.

The use of regression models for prediction of crop yields, particularly in association with climate change, has been criticized (Biswas, 1980; Katz, 1977; Hayes et al., 1982; and Rosenberg, 1982). Major problems of this type of model include their "black-box" nature, their reliance on statistical coefficients rather than on physical relationships, and the difficulty of separating changes in yield due to climate from changes due to differences in management or technology. For the most part, regression models assume linear relationships between crop yields and environmental variables and static states of crop varieties and production technology. Despite these problems, statistical regression models have been used quite extensively for climate impact studies, usually with simple prescriptive scenarios (e.g., Waggoner, 1983; Couter and Haug, 1986; see Table III-2).

FIGURE III-11

Observed and Predicted Stem Dry Weight for Winter Wheat as Affected by Enriched CO2 at Two Moisture Regimes



Source: Chaudhuri et al., 1986.

TABLE III-2

Effect of Weather on Yields (in quintals ha^{-2}) of Corn in Three States

	Crop Region, State		
	Iowa	Illinois	Indiana
A. Variable			
Yield, Average 1978-1980	72.7	68.8	65.3
Temperature, °C			
July	--	-1.56	--
Aug	--	-0.64	--
Oct	--	0.57	--
July to Aug Average	--	--	-2.34
Precipitation, mm			
May	--	--	-0.017
Sept to June	0.013	--	--
Sept to June SDFN b/	-0.0001	-0.00006	--
July	--	--	0.045
Combined Variables			
Apr and May PET c/	-0.12	--	--
May Prec/PET	--	-1.49	--
July Prec minus PET	0.076	0.025	--
(June ET/ET d/ + July ET/ET)/2	--	--	2.27
B. Calculated Estimated Change			
Yield, quintals/ha	-2.36	-1.72	-2.80
Change from 1978-1980 average	-3%	-3%	-4%

a/ The effects are given as b coefficients in quintals/ha/unit of variable, i.e., mm of precipitation, °C of temperature or fraction of a ratio (after Leduc, 1980). B. Estimates of the change in yield with a 1°C increase in temperature and a 10% decrease in precipiation from the historic average temperature and precipitation recorded for the regions.

b/ SDFN, departure from normal precipitation, squared.

c/ PET, potential evapotranspiration in millimeters, a measure of the demand for water.

d/ ET/ET, evapotranspiration divided by average evapotranspiration.

Source: Waggoner, 1983.

4. Dynamic Process Crop Growth Models

Dynamic crop growth models are driven by climate variables and reflect current understanding of the basic relationships of crop growth and climate. They employ knowledge of the underlying physiological and morphological plant processes and the transfer of energy and mass within a crop canopy to provide prediction (and explanation) of integrated plant behavior. Loomis et al. (1979) describe this "systems approach" to crop modeling. Dynamic process models exist for almost every major crop (e.g., Stapper and Arkin (1980) for corn, Acock et al. (1985) for soybean, and Ritchie and Otter (1984) for wheat). Crop growth models are useful for studying the effects of transient climate change and for testing possible adjustments to climate change such as modified irrigation scheduling and shifts in planting date.

Crop growth models are suitable for studying the combined effects of both physiological and climatic changes due to increased trace gases (Figure III-12). A meeting of experts organized by the World Meteorological Organization (WMO) and the International Meteorological Institute in Stockholm concluded that sensitivity studies with process-based crop models and climate change scenarios are an appropriate first step in studying the impacts of increasing CO2 and changing climate on crop growth and yield (WMO, 1984). Carter et al. (1984) tested the sensitivity of crop models to daily and monthly time resolutions and found that monthly climatic variables (most GCMs provide monthly data) are adequate for some crop modeling studies. This may not always be the case, since some crop models need daily inputs of climate variables. Carter et al. also used crop models to show that if interannual variability of temperature and precipitation changes, sensitivity to short-term climatic variation may be different from sensitivity to long-term climate change.

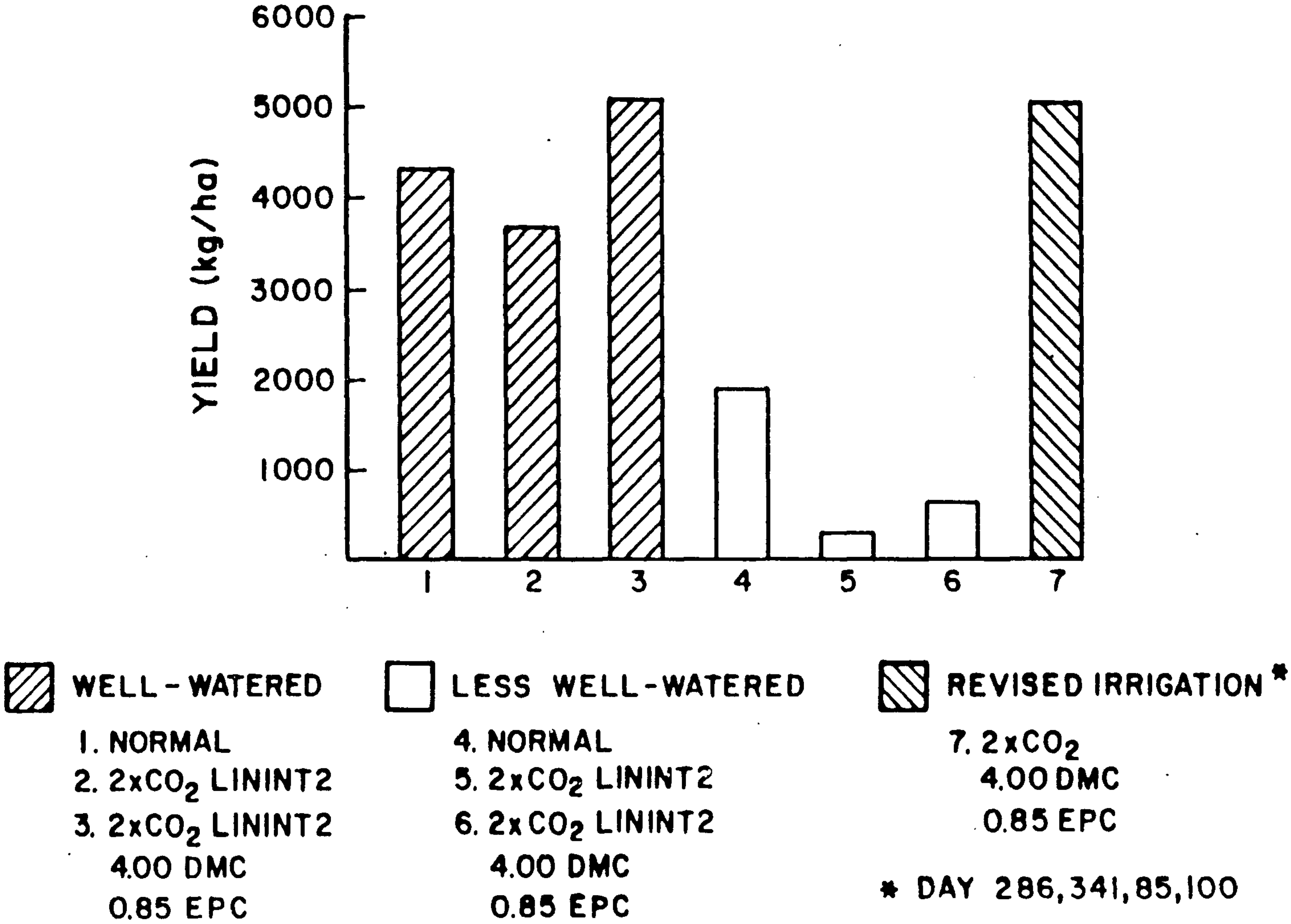
Kanemasu (1980) used a wheat model to estimate the effect of increasing CO2 and temperature on wheat yields and found a 59% increase in yield under CO2 enrichment to 500 ppm. Baker et al. (1985) adapted a crop-climate model to investigate the interactive effects of CO2, leaf area index (LAI), and the environment on midday crop water use and water-use efficiency. The simulations showed that increased CO2 in conjunction with increased LAI can offset the lowered transpiration caused by increased stomatal resistance. Couter and Haug (1986) used the CERES-Wheat model (Ritchie and Otter, 1984) in their study of the effect of climate change on agriculture in Oklahoma.

5. Probability Analyses

Several authors have emphasized the need to study changes in the probabilities of climate variables, since extreme meteorological events such as a brief span of high temperatures can have a large detrimental effect on crop yields. These climatic probabilities can then be related to effects on yield. Mearns et al. (1984) found that the relationships between changes in mean temperature and corresponding changes in the probabilities of extreme temperature events are nonlinear, and that relatively small changes in mean temperature can result in relatively large changes in event probabilities. In particular, for Des Moines the likelihood of a five-consecutive-day maximum

FIGURE III-12

CERES-WHEAT YIELDS UNDER NORMAL AND 2xCO_2 CONDITIONS



CERES-Wheat yields under normal and doubled CO2 conditions with climate scenario based on the GISS GCM doubled CO2 run alone and combined with physiological changes of increased CO2 for Cases 1-3: well- watered; Cases 4-6: less well-watered and Case 7: irrigation revised to give adequate water at all development stages.

Source: Rosenzweig et al., 1986.

temperature occurrence of at least 35°C (95°F) is about three times greater under a relatively small 1.7°C (3°F) increase in mean temperature than under current climate conditions. In regions where crops are grown under conditions that are close to the crops' maximum-temperature tolerance limits, high temperature extremes can have significantly harmful effects on crop growth and yield.

In an analysis of rainfall probabilities, Waggoner (1986) showed that 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 drought or for consecutive events like two dry months. When Waggoner analyzed the relative changes in the probabilities of low yields when rain decreases, he found that the relative change in the probability of low yield may be much more than the relative change in rain.

Parry and Carter (1985) also show that a change in the frequency of extreme events is an important indicator for analysis of climate impacts. This has implications for scenario development: the statistical characteristics of predicted future climates from GCMs should be included in scenarios rather than means alone. Parry and Carter assessed the risk of crop failure resulting from low levels of accumulated temperature for oats farming in southern Scotland and concluded that minor climatic variations in the United Kingdom have induced substantial changes in magnitudes of agricultural risks (Figure III-13).

6. Integrated Agricultural and Economic Studies

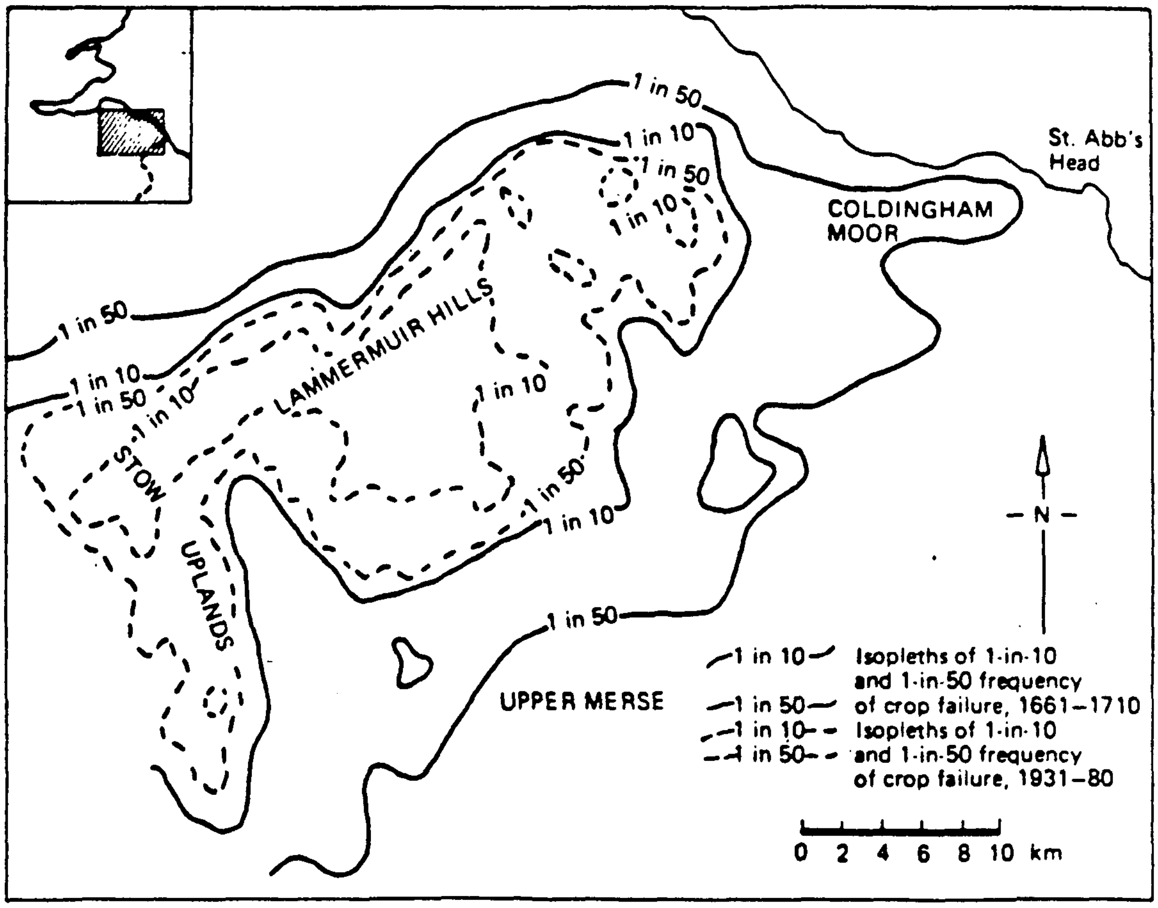
The scales of integrated studies range from individual farms to regional agricultural economies, the national agricultural sector, and finally to the global food trade. These studies seek to describe how the effects of climate change may reverberate throughout some or all of these scales.

Callaway et al. (1982) analyzed methods and models for assessing the economic impacts of CO2-induced climate change on the U.S. agricultural economy. Their principal finding was that there would be widespread impacts throughout both the agricultural sector and the economy in general. They emphasize that model studies should be used to analyze the sensitivity of various sectors of the economy to a range of climate change impacts. These analyses should then be useful when considering possible long-term adjustments.

Couter and Haug (1986) examined the impacts of a climate change scenario on the agricultural sector of the Oklahoma economy. They used a climate scenario with an average 10% decrease in April through September precipitation, but specified that it would derive from rainfall events of 0.01-0.50 inches occurring in a 24-hour period. Using both statistical regression and crop growth models and an input/output economic model, they showed that the climate scenario they postulated would cause a loss of $86 million in winter wheat income and a total decrease of $327 million in state economic output (Table III-3).

FIGURE III-13

Crop Failure Risks



Locational shift of a high-risk zone between the cool (1661-1710) and warm (1931-80) periods. Risk is expressed as frequency of oats crop failure.

Source: Parry and Carter, 1985.

TABLE III-3

Average Annual Impacts Resulting from Climate Change Hypothesis for Oklahoma

Impacted Sector (Activity)	Average Annual State Level Impacts
Precipitation (area weighted)	-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	+0.40**
Irrigation Water Demand	+0.41 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.

** Analysis of small region.

Source: Couter and Haug, 1986.

Parry et al. (1986) reviewed results of integrated studies for several crops and areas of the world including Canada, Iceland, Finland, USSR and Japan. Doubled CO_2 climate changes specified for Canada from the GISS GCM (Table III-3) resulted in decreases in total provincial wheat production, of 20%, 22%, and 33%, depending on soil type, and reductions in total provincial farm income, employment, and household purchasing power. Results of other experiments in Japan (rice), USSR (oats, rye, barley), Finland (barley), and Iceland (hay) further demonstrate the complexity of effects of climate change on agricultural systems, including regional variations and potential impacts of shifts to new varieties.

E. FUTURE DIRECTIONS FOR RESEARCH AND CLIMATE IMPACT ANALYSIS

The goals of climate change studies for agriculture are (1) to determine the nature and range of the possible impacts; (2) to understand the potential interactions among the impacts; and (3) to provide a basis for consideration of possible means for preventing, adjusting to, or alleviating any negative consequences of the changes. An additional goal should be to frame alternatives for national and international agricultural strategies and environmental policies. An initial objective should be to increase societal flexibility in creating potential responses.

1. Global Studies

Existing global agricultural assessments, while providing us with valuable information on the potential effects of climate change on agriculture, suffer from a number of limitations, as described by Liverman (1986) in a paper prepared for the International Institute for Applied Systems Analysis. Several of Liverman's conclusions about current agricultural assessments are appropriate here. They:

- lack good meterological and agricultural data, particularly on subsistence production;
- fail to consider climate change as a change in climate variability (hence affecting agricultural risk) rather than just changes in the mean climate;
- fail to provide estimates of the uncertainty associated with assessments; and
- fail to incorporate the possibility of technological change or governmental intervention, which may alter the vulnerability of global agriculture.

2. Research Directions

Important future directions of studies on how climate change affects agriculture should include:

- Focusing on transient climate change scenarios rather than predicted future equilibrium climates in agricultural studies. Analyses of potential annual or 10-year agricultural shifts offer an opportunity to build on previous static analyses based on a step-change to a doubled CO2. Collaborating studies between GCM modelers, the agricultural research community, and climate change impact analysts are needed so that GCM output of key variables is compatible with users' needs; for example, daily climate output is necessary for some crop growth models, and probabilities of extreme climatic events are often critical to economic decisions. On the other hand, impact analysts can benefit from the understanding of changing climate provided by the GCM modelers.

- Continuing development of climate, crop, water-use, and economic models. Previous studies should be repeated with the improved models, and the results compared and contrasted with previous results.

- Integrating climate, crop, water-use, and economic models in order to study the cascade of climate change effects through the entire range of interest, from environmental impacts to shifts in agricultural land use, and to global food supply and demand. Integrated models should also be used to study the combined climatic and physiological effects of trace gases on crop growth.

- Developing policy analyses to study alternative adjustment strategies aimed at increasing the flexibility of society's responses to climatic changes.

F. SUMMARY

Given the caveats that must accompany any predictions of an uncertain future, the following conclusions about the effects of atmospheric trace-gas-induced climate change on agriculture may be drawn: at the field level, the major physical processes affected will most probably be the thermal and water regimes and the levels and timing of pest infestations. Stresses caused by changes in these processes can all have detrimental effects on crop yields. For plant breeders, there will be demand for more heat- and drought-tolerant crops. If climate change occurs to the extent predicted by the GCMs, shifts in farming systems and cropping patterns will occur. These shifts will have impacts on local economies and environments -- sensitive ecosystems may be threatened. Climate change effects on agriculture will eventually be felt at regional, national, and international levels.

Methods for studying climate change and agriculture are improving as climate, crop growth, and economic models continue to be developed. Study of the transient climate, rather than equilibrium climate, and its effects should be emphasized, as should the impact of changes on frequency of climate extremes. The goals of climate change impact research are to define more clearly the ranges of possible impacts and to engender flexibility in society's reponses to them. As the models improve, impact studies should be iterated, integrated, and expanded to include testing of possible responses to the potential effects. In this way, improved information will be developed for future policy decisions.

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IV. EFFECTS ON WATER RESOURCES

Prepared by:
Peter H. Gleick

A. FINDINGS

1. There is evidence that climate change since the last ice age (18,000 years B.P.) has significantly altered the location of lakes, although the extent of present-day lakes is broadly comparable with 18,000 years B.P. For example, there is evidence indicating the existence of many tropical lakes and swamps in the Sahara, Arabian, and Thor Deserts around 9-8,000 years B.P.

2. The inextricable linkages between the water cycle and climate ensure that potential future climate change will significantly alter hydrological processes throughout the world. All natural hydrological processes--precipitation, infiltration, storage and movement of soil moisture, surface and subsurface runoff, recharge of groundwater and evapotranspiration--will change if climate changes.

3. As a result of changes in key hydrological variables such as precipitation, evaporation, soil moisture, and runoff, climate change is expected to have significant effects on water availability. Early hydrological impact studies provide evidence that relatively small changes in precipitation and evaporation patterns might result in significant, perhaps critical, changes in water availability. For many aspects of water resources--including human consumption, agricultural water supply, flooding and drought management, groundwater use, and recharge and reservoir design and operation--these hydrologic changes will have serious implications.

4. Despite significant differences among climate change scenarios, a consistent finding among hydrologic impact studies is the prediction of a reduction in summer soil moisture and changes in the timing and magnitude of runoff. Winter runoff is expected to increase and summer runoff will decrease. These results are robust across a range of climate change scenarios.

5. Future directions for research and analyses suggest that improved estimates of climate variables are needed from large-scale climate models, innovative techniques are needed for regional assessments, increased numbers of assessments are necessary to broaden our knowledge of effects on different users, and increased analyses of the impacts of changes in water resources on the economy and society are necessary.

B. INTRODUCTION

The growing concern in the scientific community about the effect of global climate changes on water availability has stimulated research into appropriate methods for evaluating such hydrologic alterations. There have also been a number of case studies of possible regional hydrologic changes based on plausible future climatic changes. This work involves such diverse academic fields as climatology, surface hydrology, atmospheric chemistry, and dynamics of water-management systems. Because of the many implications for society of changes in global climate and subsequent changes in water quantity and quality, there is room for a significant expansion both in the areas and in the methods of study of the hydrologic impacts of climatic change.

There are many possible methods for analyzing changes in water-resource availability due to climatic changes -- methods that depend on a wide variety of variables, including the hydrometeorological characteristics of a region, the types and timing of existing and expected water demands, and the interests and goals of the researcher. A review of the major works to date is an appropriate introduction to the problems and pitfalls facing climatologists and hydrologists, as well as to the strengths and weaknesses of a number of possible research methods.

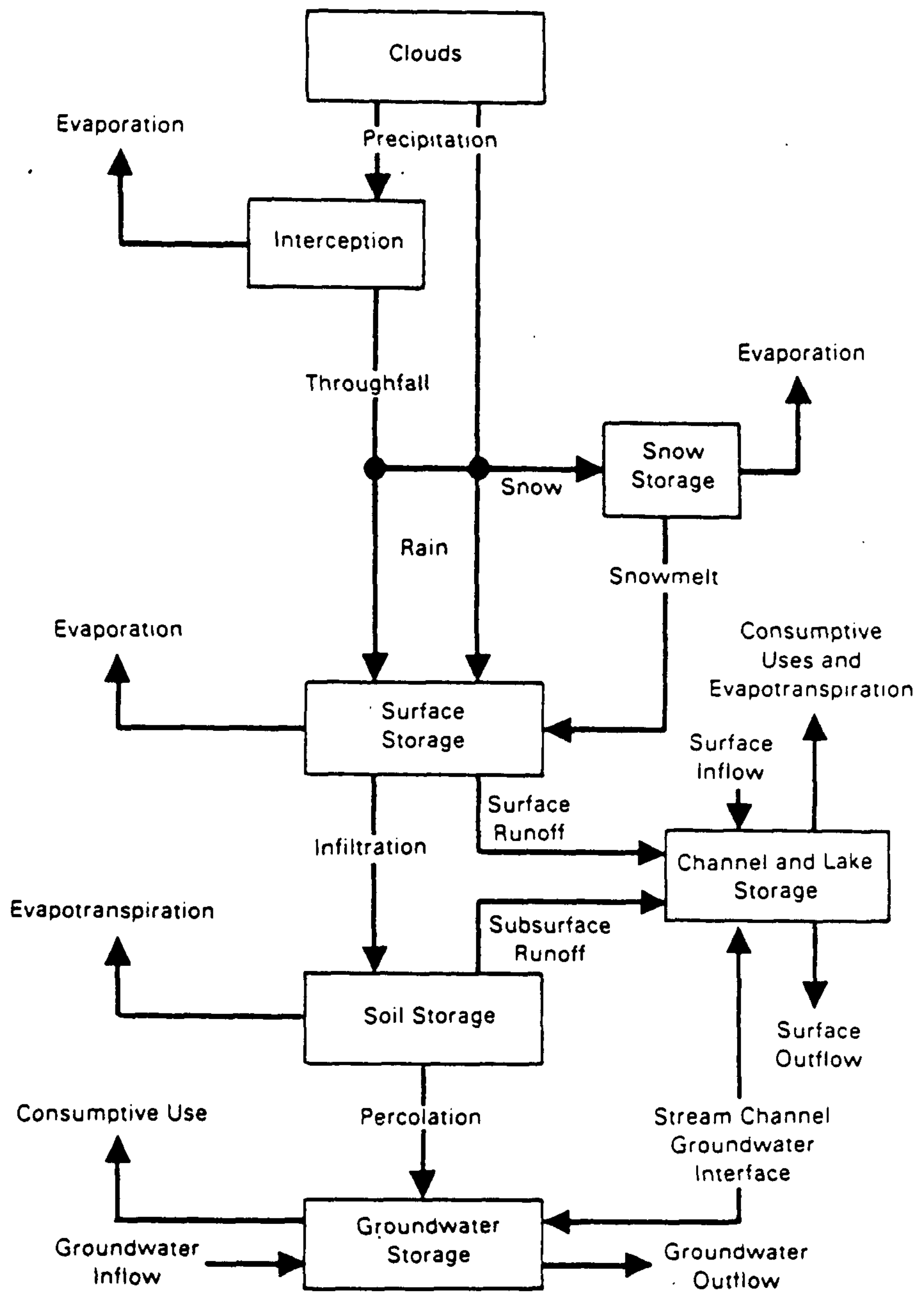
1. Importance of Water Resources

Water resources, essential to the survival of civilization, are significantly affected by climate. All natural hydrologic processes (precipitation, infiltration, storage and movement of soil moisture, surface and subsurface runoff, recharge of groundwater and evapotranspiration) are affected (Figure IV-1). Certainly alterations in these hydrologic cycles will result in significant changes in water availability. Because of the intimate linkages between the water cycle, vegetation, and climate, the full range of water-resource issues can be expected to respond to climate change. These water-resource issues and their sensitivity to climate change are listed in Table IV-1, drawn from a Department of Energy report (DOE 1985). The importance of climate change in water resources is further described in a 1984 EPA report:

> As part of their jobs water planners, coastal engineers, and agronomists necessarily make assumptions about future water-resource supplies, temperature, droughts, and storms. In general, they assume that in the future these conditions will repeat those of the past -- there will be the same amount of water available, the worst storm during the next hundred years will be similar to the worst storm during the past 100 years, and droughts will be of similar frequency and duration... Unfortunately, the underlying assumption that future climate change will essentially repeat the past no longer appears valid (U.S. Environmental Protection Agency, 1984, p. i).

FIGURE IV-1

Schematic Diagram of the Hydrologic System of a Drainage Basin



Source: Callaway and Currie, 1985.

Finally, there is substantial evidence, based on paleoclimatic data, that demonstrates the important linkages between climate and hydrological systems. Because accurate climatic records extend back only a few hundred years, most information about earlier climatic trends must be obtained from a variety of geophysical sources, including tree-ring analysis (Stockton and Meko 1983), archaeological evidence (McGhee 1981), and physical indicators of lake levels (Street-Perrott and Harrison 1985). Nicholson (1986) reviews some of this information and concludes that it is possible to document some significant changes in water availability on an historical time scale, but that no consistent regional pattern of increased or decreased rainfall can be associated with a change in global temperatures.

Nicholson's study of climatic history -- drawing from available data such as landscape descriptions, drought, flood and harvest information, and climate and weather descriptions -- observes that the Altithermal period of ca. 6000 B.P. provides an historical analog to projected global warming. During this period, 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. These conditions are thus similar to model projections for global warming, yet Nicholson cautions that firm predictions cannot be made given that similar rainfall conditions occurred during periods of globally reduced temperatures. Nicholson concludes that changes in rainfall and water resources could be gradual or abrupt, involving changes of mean conditions, variability about the mean, or seasonality. Any of these changes might have severe impacts on populations. Webb and Wigley DOE (1985) however have reviewed the literature and argue that there is little evidence for a "global" altithermal period 6000 years ago. They suggest that there is evidence for local warmth that was probably less than 1°C when averaged over the globe. Hence, the period 6000 B.P. may not be a good analog to projected global warming.

Kutzbach and Street-Perrott (1985) provide evidence that climate change since the last ice age (18,000 years B.P.) has significantly altered the location of lakes--although the extent of present-day lakes is broadly comparable with that existing in 18,000 years B.P. At the last glacial maximum, lake levels in the northern tropics were low and falling. This trend continued until 12,500 years B.P. when water levels began to rise, and eventually culminated in many lakes and swamps in the Saharan, Arabian, and Thor Deserts around 9,000-8,000 years B.P. Approximately 6,000-5,000 years ago, drying out set in and the current population of lakes evolved.

2. Scope of this Study

This section will address the following major questions regarding climate change and water resources:

1. What hydrological impact studies have been conducted thus far and what do they say about potential effects of climate change on water resources?

TABLE IV-1

Potential Sensitivity of Water Resource Issues to CO2 Buildup

Issue	Potential Sensitivity to CO2 Buildup
Inadequate Surfacewater Supply/Storage	HIGH
Groundwater Mining	
Conflicts in Use	
Water Losses from Storage Systems	
Vegetation Management	
Drought	
Flooding	
River Sedimentation	
Salinity Problems	
Waterlogging of Soils	
Saline Intrusion of Aquifers	
Surfacewater Contamination	
Effects of Land Use Change on Basin Hydrology	MODERATE
Acidification of Lakes	
Waterborne Diseases	
Eutrophication	
Inefficient Irrigation Practices/ Management	
Navigation Problems	
Reservoir Sedimentation	
Groundwater Contamination	
Effect of Changing Lake Levels on Aquatic Ecosystems	LOW
Conveyance Losses	
Availability of Potable Water	
Inadequate Water Treatment Facilities	
Channel Scour/Channel Erosion	
Groundwater Infiltration into Municipal Sewer Systems	

2. What criteria should be applied to the evaluation of regional hydrologic models to assess their strengths and weaknesses?

3. What are the future research directions needed to expand our knowledge of hydrologic impacts of climate change?

C. GENERAL CIRCULATION MODELS AND HYDROLOGY

Climate models sometimes include a mathematical description of surface hydrological processes. Yet even state-of-the-art General Circulation Models (GCMs) use parameterizations of surface hydrologic processes that are greatly simplified compared with actual hydrologic processes. While advances in parameterizations of hydrologic processes can and will no doubt be made, major improvements in such parameterizations may be slow in developing (Dickinson 1984). In particular, the complexity of small-scale surface processes is now only poorly represented by climate models whose surface resolutions are too coarse to account for such small-scale phenomena. As a result, improvements in modeling soil hydrology, the effects of vegetation, and other detailed hydrologic factors will continue to be limited by a lack of adequate data sets of important surface variables.

The prospect of global warming presents the potential for changes in certain critical hydrologic variables -- precipitation and evapotranspiration -- and thus raises the possibility of major regional water-supply problems, including changes in runoff and soil-moisture patterns. Budyko and Vinnakov (1977), Manabe et al. (1981), Mitchell (1983), and Manabe and Wetherald (1986) have suggested that major reductions in summer soil-moisture patterns in the middle latitudes are a possible outcome of a doubling of atmospheric carbon dioxide. Results from Washington and Meehl (1984) show different changes in zonal-mean soil-moisture values associated with changes in the timing of precipitation, the timing and magnitude of spring runoff, and increased soil-moisture supplies during the summer months. In their study, positive feedbacks among soil moisture, precipitation, and low clouds are associated with the persistence of soil moisture through the summer months.

Soil-moisture changes are thus possible in some of the most productive agricultural areas of the world. Significant persistent changes in soil moisture in these regions, whether the changes are manifested as increases or decreases, would have serious societal consequences. In order to evaluate these changes, more detailed evaluations of regional hydrologic effects are needed than can be accomplished solely with existing models.

We are thus faced with a dilemma: those tools capable of providing information on the likely effects of human activities on global climate are at present unsuited for evaluating the nature and magnitude of important regional effects. Yet information on regional effects is important for determining appropriate policy responses to climatic changes. Until realistic surface hydrology can be incorporated into general circulation models with adequate resolution, evaluations of regional and local hydrologic effects must be accomplished through other methods.

D. POTENTIAL EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES

In the last decade, there have been a number of analyses of the relationship between water resources and global climatic change. This section reviews the most important and informative of these analyses and discusses approaches that (1) take advantage of the strengths of GCMs and (2) permit more detailed regional assessments than can be accomplished with GCMs alone. Studies that have evaluated the regional hydrologic implications of climatic changes include those of Schwarz 1977, Stockton and Boggess 1979, Nemec and Schaake 1982, Revelle and Waggoner 1983, U.S. Environmental Protection Agency 1984, Flaschka 1984, Novaky et al. 1985, Gleick 1986a, 1986b, 1986c, Cohen 1986, and Mather and Feddema 1986. These works provided the first evidence that relatively small changes in regional precipitation and evaporation patterns might result in significant, perhaps critical, changes in regional water availability. The following section reviews the methods, results, strengths, and limitations of these works.

In one of the earliest comprehensive studies, Schwarz (1977) looked at existing hydrologic conditions in the northeastern United States and attempted to evaluate the effects on water supply of hypothetical climatic changes. Schwarz considered three approaches: (1) a review of individual water-supply systems and their previous responses to climatic anomalies; (2) a general speculation about the effects of climatic changes on a series of broad hydrologic criteria; and (3) a first attempt using synthetic streamflows to evaluate the effect on reliable water supply from hydrologic variations that may result from climate change. Even in the absence of estimates of likely climatic change, Schwarz concluded that certain characteristics of water supplies, particularly the variability of streamflow, are very sensitive to changes in climate. He also concluded that a full understanding of the relationships between climatic changes and water supply, not yet achieved, is a desirable goal and that a range of likely climatic-change scenarios should be available to water-resource planners.

Stockton and Boggess (1979) built upon the classic empirical relationships between precipitation, temperature, and runoff developed by Langbein and others (1949), to evaluate the hydrologic effects of hypothetical changes in both temperature and precipitation. Stockton and Boggess analyzed four climate scenarios, involving changes of +2°C and -2°C in temperature and changes of +10% and -10% in total annual precipitation, in order to estimate the resulting changes in the average annual runoff of major water basins throughout the United States. They concluded that a change toward a warmer and drier climate would have the greatest impacts nationwide, with the most severe effects in western, water-limited regions. The most beneficial effects would result from a change to cooler and wetter conditions, although there would be negative consequences from increased flooding on most major river systems. Although this important work had a large geographical scope and thus excluded considerable temporal, physical, and hydrologic detail, it was one of the first studies to raise the possibility of non-linear hydrologic responses to climatic changes.

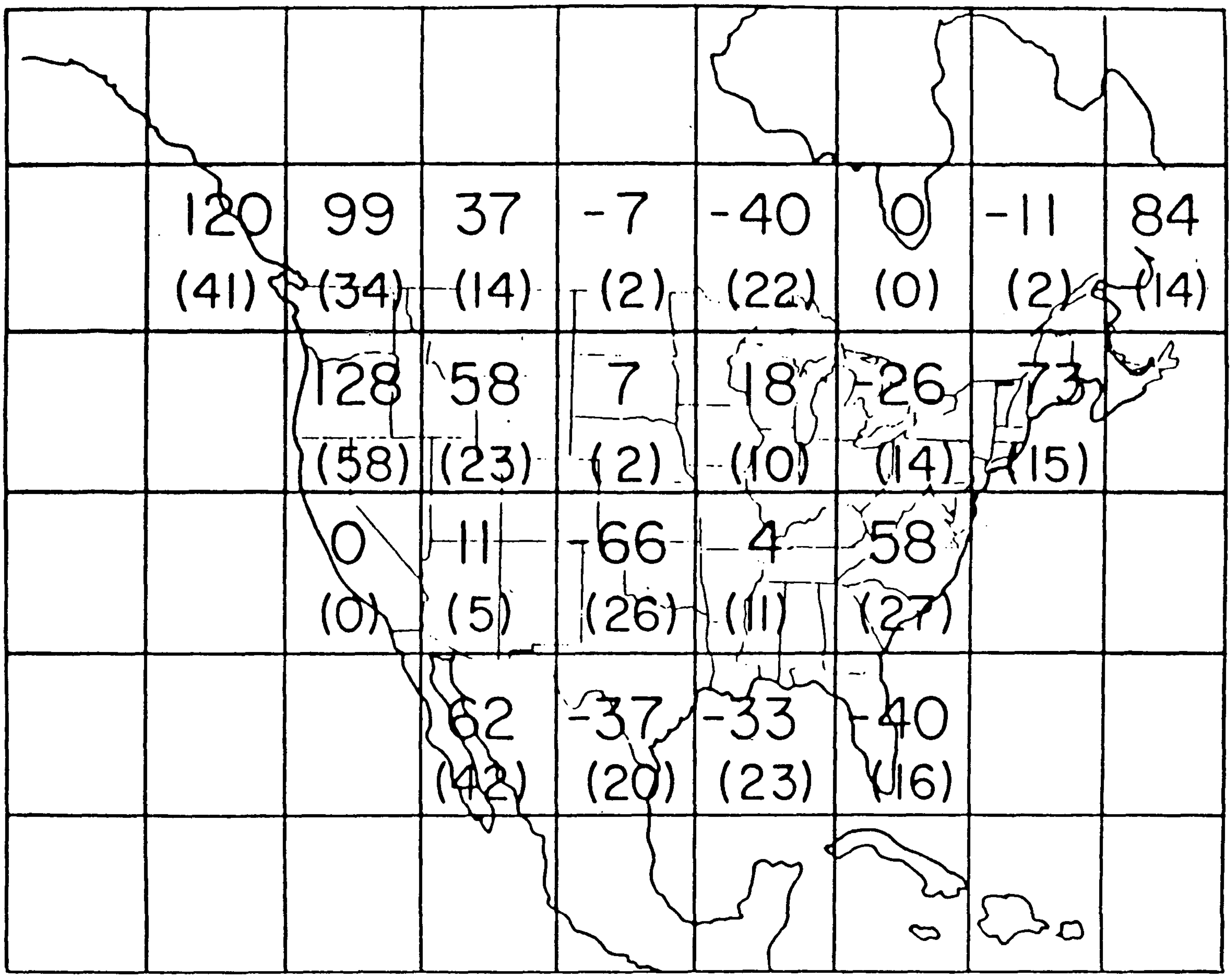
Nemec and Schaake (1982) also used hypothetical climate-change scenarios to evaluate the influence of climatic variations on runoff. Significant changes in runoff in both an arid and a humid watershed were shown to result from only moderate variations in climate -- specifically, slight changes in temperature and precipitation. Moreover, such climate variations had major impacts on the design and operation of reservoir storage. They concluded that the serious impact of changes in runoff suggested by their models substantiates the need for further consideration of the effects of climate change on the design and operation of water-resource systems in different climatic regions of the world. In a recent follow-up to the Nemec and Schaake work, Klemes (1985) reviewed the role of hydrologic models and provided an excellent discussion of the types of studies that should provide the most useful information on the sensitivity of water resources to variations in climate. Klemes also discussed the types of tests that should be applied to certain types of hydrologic models to ensure that significant results are obtained (or that insignificant results are discounted).

Revelle and Waggoner (1983), like Stockton and Boggess (1979), used the statistical correlations among temperature, precipitation, and runoff from Langbein and others (1949) to evaluate the effects of hypothetical changes in precipitation on runoff in the western United States, particularly in the Colorado River Basin. In their study, they showed that warmer air temperatures and slight decreases in precipitation could reduce severely both the quantity and the quality of western U.S. water resources. Using multiple correlations among historical precipitation, temperature, and runoff in the Colorado River Basin, they then evaluated the consequences of a 2°C increase in temperature and 10% increases and decreases in precipitation. From these relationships, it appears that the mean annual runoff of the Colorado River Basin has been very sensitive to changes in precipitation. If such effects are valid under conditions of future climate changes, some significant consequences for water resources may occur. Whether or not such effects are seen when the temporal resolution is increased to a seasonal or monthly level remains to be evaluated. This study adds further evidence to support previous suggestions of a non-linear relationship between changes in precipitation and changes in runoff.

In one of the first attempts to use data from large-scale general circulation models, rather than purely hypothetical scenarios, the U.S. Environmental Protection Agency (1984) examined aggregate measures of changes in the hydrologic cycle under steady-state doubled atmospheric concentrations of carbon dioxide. The EPA study used coarse-resolution output from the Goddard Institute for Space Sciences (GISS) model to look at changes in precipitation, evaporation, runoff, and soil moisture over large regions of North America. Despite the acknowledged limitations of the EPA report, including the coarse resolution of the GCM and the crude reproduction of actual hydrologic and climatic characteristics in many areas, this study reaffirmed earlier suggestions that climatic changes may cause substantial changes in runoff and soil-moisture patterns in the Northern Hemisphere. Figure IV-2, taken from the EPA report, shows the change in runoff over land, along with the percentage change from the control run. The general pattern shows increased runoff in the northwest and southwest, with decreases in the

FIGURE IV-2

Changes in Runoff for Doubled CO2



Change in runoff between the last ten years of the doubled CO2 run and the last ten years of the control run, for the annual average. The top number indicates the actual change (mm), the bottom number in parentheses gives the percentage change relative to the control run.

central and eastern regions. Figure IV-3 shows the monthly variation in precipitation, evaporation, and runoff as the change from the control run values for a grid box that includes all or parts of such states as Idaho, Washington, and Oregon. The results indicate an increase in the hydrologic cycle as increases are shown for all three parameters in all months except September and April.

Flaschka (1984) used regional modeling techniques to evaluate the hydrologic effects of climatic changes in the Great Basin of the United States. This study, like that of Nemec and Schaake (1982), directly used hydrologic-modeling techniques to evaluate hypothetical climatic changes, although the author's modeling methods differ from those of Nemec and Schaake in certain important respects. Flaschka applied water-balance techniques to four watersheds in the Great Basin to evaluate the consequences of the same types of climate-change scenarios studied by Stockton and Boggess (1979) and Revelle and Waggoner (1983). She concluded that such changes could result in decreases in annual-average runoff of over 50 percent for precipitation decreases of 25 percent coupled with temperature increases of 2°C. While this study was one of the first to use regional water-balance modeling techniques, it suffered from some significant limitations, including problems with input data for model verification, the lack of algorithms for handling snowfall and snowmelt, and lack of sufficient historical unimpaired runoff values for those rivers in the basin that are heavily regulated. Two of the consequences of these drawbacks are the inability to model monthly or seasonal flows and a limited ability to verify model accuracy using historical data. Despite these problems, this study marks a major improvement over the earlier use of statistical, non-physically-based approaches.

A review published in 1985 (Novaky et al. 1985) offers a detailed framework into which integrated climate/water-resource/societal impact studies might be most conveniently organized. Although this paper is a purely qualitative study of the hydrologic impacts of future climatic change, it offers the first good outline of the elements of a complete hydrologic impact assessment. The authors discuss the importance of transforming physical water availability into economic and social values and emphasize the importance of the role of water-management techniques in reducing the social impacts of changes in water availability. Also emphasized is the importance of understanding the time-scales and sensitivities of different hydrologic factors. These points are discussed further in Gleick (1986b).

A recent review of the literature (Beran 1986) provides valuable information on various approaches for evaluating the changes in the availability of water resources from climatic changes. Table IV-2, taken from Beran's paper, summarizes the hydrological models used to determine hydrological and water-resource sensitivity due to particular climate scenarios. Beran also discusses the advantages and limitations of each type of hydrological model, as well as research requirements and topics. No preference is stated for any particular model because each method has its strengths and weaknesses. Beran also stresses caution in using existing information on future changes because improvements continue to be made in the treatment of oceans, clouds, and soil moisture within large-scale climate

FIGURE IV-3

Change in Precipitation (P), Evaporation (E) and Runoff (R) Between the Doubled CO2 Run and the Control Run as a Function of Month for Idaho, Washington and Oregon

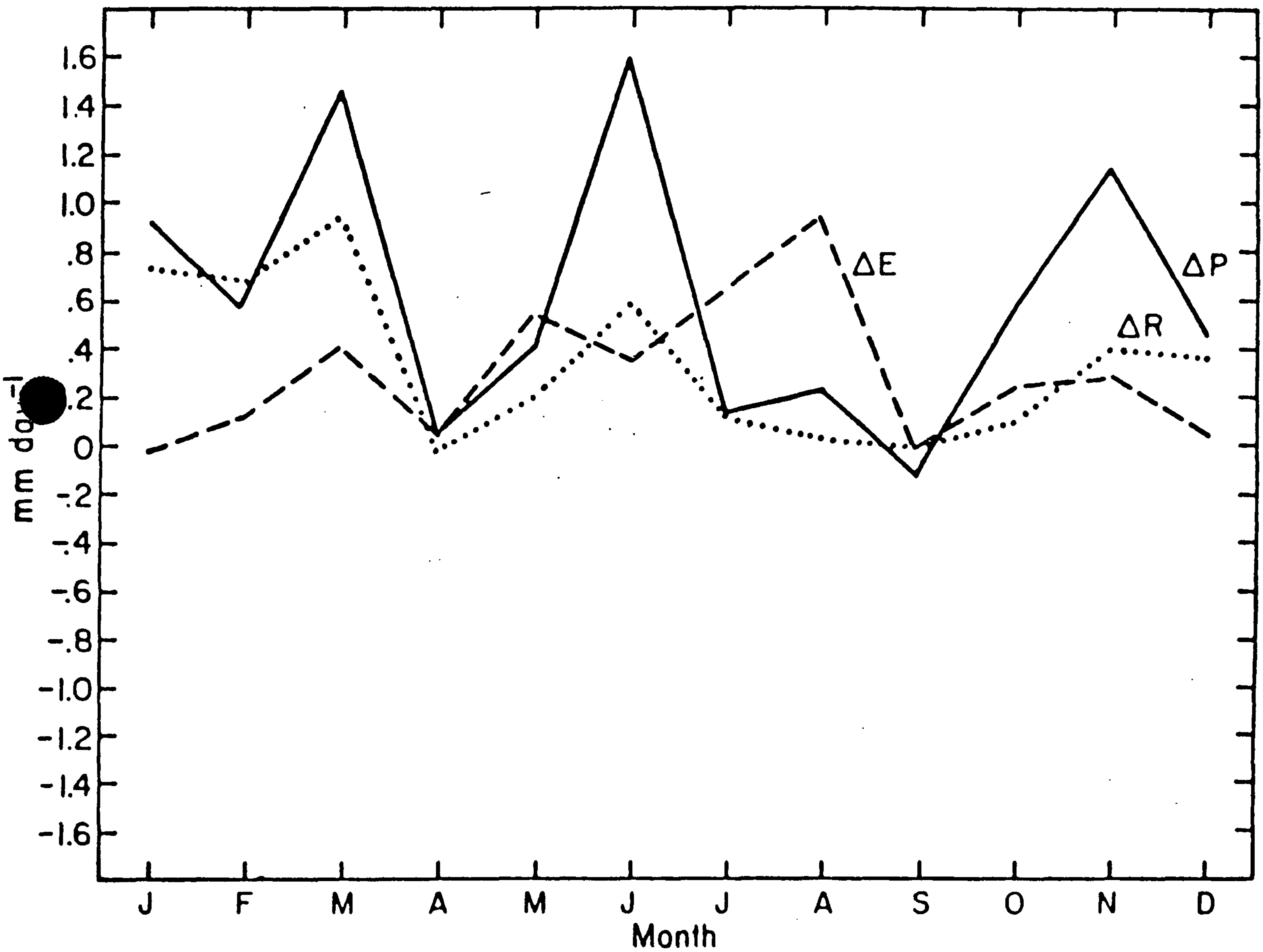


TABLE IV-2

Summary of Hydrological Models Used to Determine Hydrological and Water Resource Sensitivity or Impact Due to Particular Climatic Scenario

Type of Model	Name of Model Author and Year	Input	Output	Application
Causal/ Physics Based	Schnell (1984) based on Brigg's biomass model	Met. a/ T.S. b/	Runoff T.S.	Average climatic runoff over Europe
	Combination Aston (1984)	Met. T.S.	Runoff T.S.	Transpiration reduction effect
Conceptual	Sacramento Nemec et al. (1982)	Met. T.S.	Runoff T.S.	Sensitivity of annual runoff and reservoir yield
	SHOLSIM Aston (1984)	Met. T.S.	Runoff T.S.	Transpiration reduction effect
Empirical	Regression Beard et al. (1979)	Met. T.S.	Runoff T.S.	Annual runoff sensitivity
	Historic contrast Beran (c.f.) c/	Runoff T.S.	Runoff M.V.	Response to recent warming
	Evaporation model Cohen (1986)	GCM T.S.	Runoff T.S.	Great Lakes basin runoff
	Simulation Schwartz (1977)	Synthetic runoff	Storage M.V. d/	Reservoir sensitivity to runoff change
	Storage yield Beran (1984)	Runoff M.V.	Storage M.V.	Reservoir sensitivity to runoff change

TABLE IV-2 (Continued)

Type of Model	Name of Model Author and Year	Input	Output	Application
Water Budget	Rain-runoff Stockton (1979)	Met. M.V.	Runoff M.V.	Annual runoff sensitivity
	Idso et al. (1984)	Met. M.V.	Runoff M.V.	Transpiration reduction effect
	Subtractive model Wigley et al. (1985)	Met. M.V.	Runoff M.V.	Average runoff sensitivity
	Proportional model Beran (c.f.)	Met. M.V.	Runoff M.V.	Average runoff sensitivity

a/ Met. means meteorological inputs required such as precipitation, evaporation, radiation.

b/ T.S. means time series data input or output.

c/ Beran (c.f.) means reference is to this report.

d/ M.V. means mean (and other statistics) input or output.

models. Finally, Beran supports the use of paleoclimatology to help produce information on past climatic analogs. Such analogs may provide clues to existing hydrologic sensitivities.

Cohen (1986) looked at the implications of climatic changes on the Great Lakes region, with a particular emphasis on the long-term effect of higher temperatures and precipitation changes on lake water levels. Using basin-wide data from two general circulation models, Cohen used a simple water-balance model and a lake evaporation model to evaluate changes in lake levels and "net basin supply" -- the difference between inflow from precipitation and runoff and outflow from lake evaporation. Preliminary results shown in Table IV-3 indicate that there would be a significant decline in mean net basin supply for the Great Lakes which may be partially attributable to increases in lake evaporation. These results, however, "are highly dependent on assumptions about wind speed over the lake, and lake surface temperatures" -- two variables about which there remains considerable uncertainty. Cohen, like Novaky et al. (1985), emphasizes the need for assessments of the societal impacts of CO_2-induced hydrologic changes, and presents an outline for evaluating impacts on the Great Lakes region (see Figure IV-4). Cohen does not address either the difficulties of doing consistent quantitative comparisons across diverse areas or the need to develop reliable impact indicators -- two significant problems that will have to be addressed in later works.

Mather and Feddema (1986) apply large-scale water-balance techniques to major regions of the earth's surface and calculate changes in four water budget factors of prime interest--annual potential evapotranspiration, precipitation, water deficits, and soil water surpluses--using precipitation and temperature data from general circulation models. Table IV-4, taken from Mather and Feddema, shows changes in these four factors based on modeled changes in temperature and precipitation from both the Geophysical Fluid Dynamics Laboratory (GFDL) and Goddard Institute for Space Sciences (GISS) models. The results indicate a reasonable agreement between the two models, showing an increase in potential evapotranspiration in all regions investigated. Precipitation is found to increase in the majority of the regions studied, but these increases are generally smaller than the increases in potential evaportranspiration. As a result, annual water deficits (the ratio of actual evapotranspiration to potential evapotranspiration) increase in most of the regions.

The continued use of these approaches has both advantages and disadvantages. The principal limitation is the lack of detail about important, basin-specific characteristics that play major roles in determining actual water availability: snowfall and snowmelt, groundwater storage, vegetative effects, storm runoff, and so on. Perhaps the major advantage of this sort of large-scale assessment technique is its ability to identify regions of hydrologic sensitivity where only marginal changes in temperature or precipitation may lead to more significant, non-linear hydrologic responses.

TABLE IV-3

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

	GISS	GFDL[a]
Temperature Change	+4.3 to +4.8°C	+3.1 to +3.7°C
Precipitation	+6.4%	+0.8%
Actual Evapotranspiration	+18.1%	+6.7%
Snowmelt	-45.9%	-35.8%
Runoff	-10.9%	-8.2%
Soil Moisture Deficit (Summer)	+116.4%	+166.2%
NBS[b] (Present Normal Winds)	-20.8%	-18.4%
NBS -- Consumption Use (2,035 proj.)	-28.9%	-26.4%
NBS (80% Winds)	-4.1%	-4.0%
NBS (80% Winds) -- Consumption Use (2,035 proj.)	-11.8%	-11.7%

[a] GFDL = Geophysical Fluid Dynamics Laboratory

[b] NBS = Net Basin Supply

Source: Adapted from Cohen (1986a).

FIGURE IV-4

Great Lakes Impacts Study

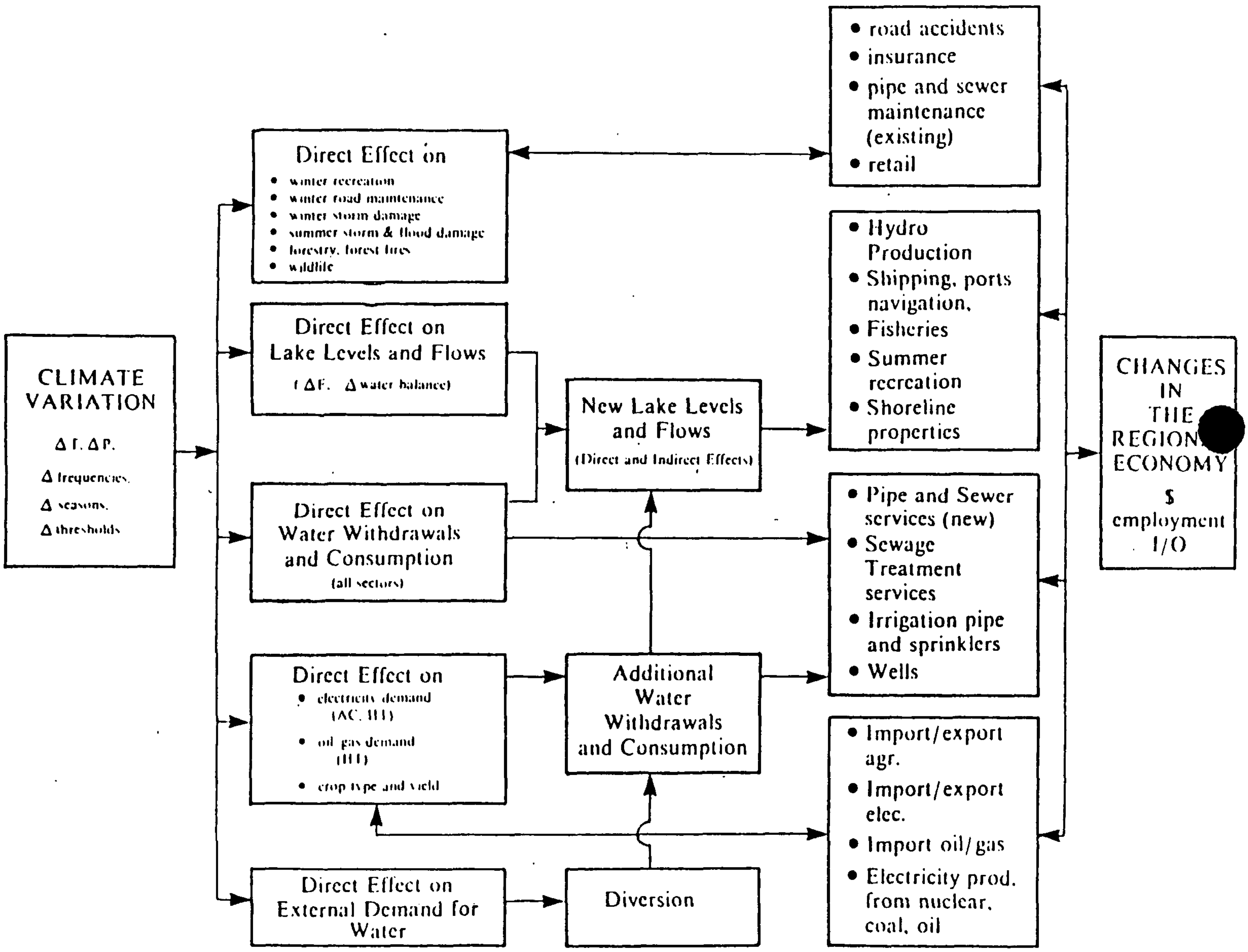


TABLE IV-4

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	Annual Potential Evapotranspiration		Precipitation		Water Deficit		Water Surplus	
	GFDL	GISS	GFDL	GISS	GFDL	GISS	GFDL	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	-46
Pacific Northwest	171	122	62	92	142	61	32	32
Ukraine (USSR)	153	97	98	136	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

Source: Mather and Feddema, 1986.

A series of papers by Gleick (1986a, 1986b, and 1986c) discuss in far greater detail the advantages and limitations of regional hydrologic assessment techniques, particularly water-balance techniques for intermediate-size watersheds. The ability of such water-balance models to incorporate detail on short-time scales and geophysical details excluded by larger models permits more accurate evaluations of changes in both runoff and soil moisture that would result from plausible future climatic changes. Gleick (1986b) discusses the theoretical basis for evaluating regional hydrologic impacts of global climatic changes and presents criteria for choosing appropriate methods (see Table IV-5). Water-balances methods, modified from their original formulation by Thornthwaite and Mather (1955, 1957), were then applied to a specific watershed in California that is likely to be sensitive to future climatic changes -- a criterion that Novaky et al. (1985) noted was of particular importance. A wide range of climate-change scenarios was evaluated, including both hypothetical climate changes and changes suggested by three state-of-the-art general circulation models. Gleick's most significant finding is that there are certain consistent hydrologic impacts despite significant differences among the climate-change scenarios. In particular, major decreases in available soil moisture and runoff were observed for all the scenarios, together with increases in winter runoff (Figure IV-5a,b). These changes--and the mechanisms that lead to the changes--correspond well with recent GCM hydrologic results published by Manabe and Wetherald (1986), which showed statistically significant summer soil-moisture drying in many areas. In summary, Gleicks results are consistent with Cohen and Mather, who used the GISS and GFDL models.

The works described above provide a solid foundation of both methodology and case studies upon which future research can be built. In particular, the focus on the use of regional hydrologic models (see Nemec and Schaake 1982, Flaschka 1984, Beran 1986, Cohen 1986, and Gleick 1986a, 1986b, 1986c) is the result of the difficulty of using large GCMs for small-scale hydrologic assessments. Until GCMs greatly improve their surface hydrology and their resolution, regional hydrologic assessments of future climatic changes will continue to be done using smaller, more accurate hydrologic models.

E. CRITERIA FOR USING REGIONAL MODELS TO EVALUATE CLIMATIC CHANGES

Because of the diverse modeling methods available, it would be valuable to have a set of criteria for choosing techniques for assessing the regional hydrologic effects of climatic changes. This section outlines important factors that should affect the choice of modeling methods.

To successfully use regional-scale modeling techniques to evaluate the hydrologic consequences of climatic changes, the strengths and weaknesses of the regional hydrologic models used must be well understood. Gleick (1986b) describes six important limiting technical factors that must be considered when selecting and using a regional hydrologic model to study the impacts of changes in climate on regional water resources. These factors are listed in Table IV-5 and discussed below.

TABLE IV-5

Criteria for Using Regional Hydrologic Models for Climatic Impact Assessment

1. The accuracy of the model in reproducing existing hydrologic conditions;
2. The degree to which model parameters depend upon the climatic conditions for which the model is calibrated;
3. The availability of the input data, including comparative historical data;
4. The accuracy of the input data;
5. Model flexibility, ease of use, and adaptability to diverse hydrologic conditions; and
6. Compatibility with existing general circulation models.

Source: Gleick 1986b.

FIGURE IV-5a

Percent Change in Average Summer Soil Moisture (June, July, and August) Over the Base Run for All Eight GCM Scenarios

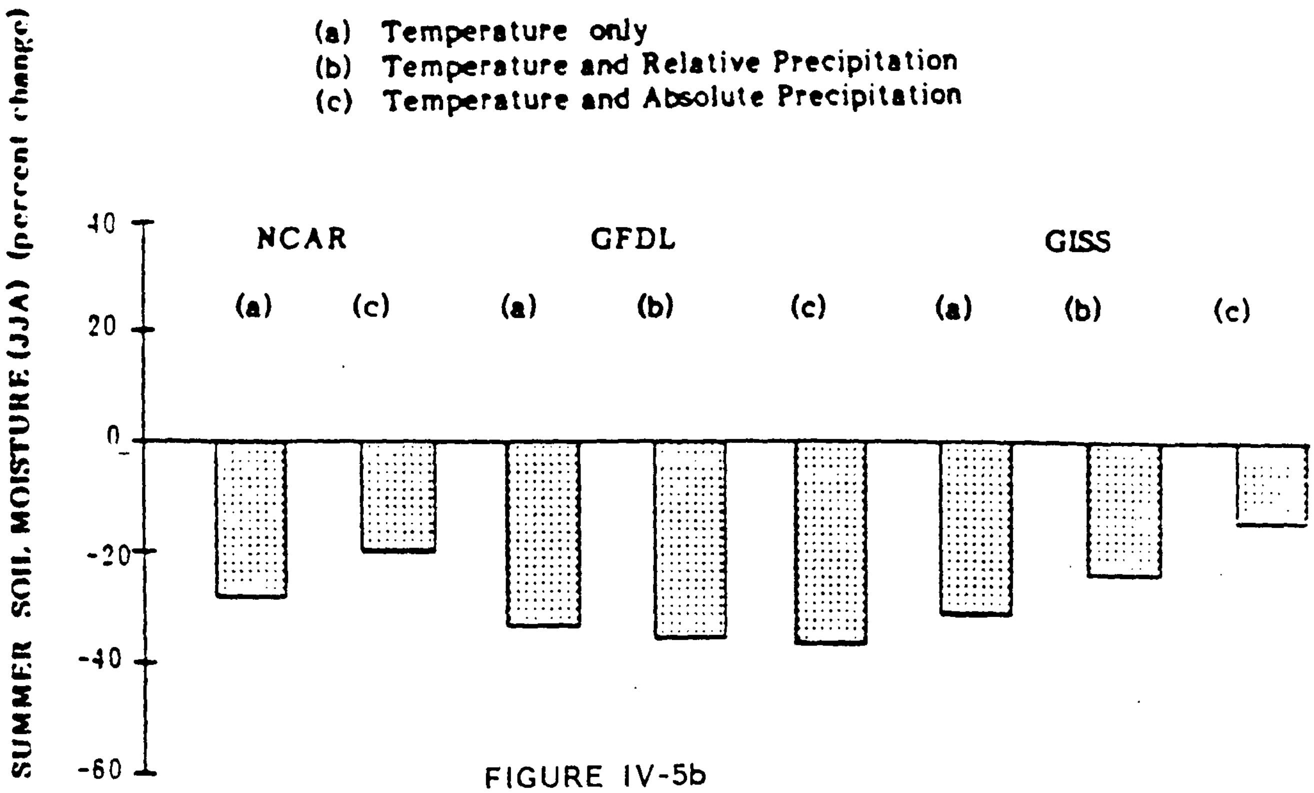
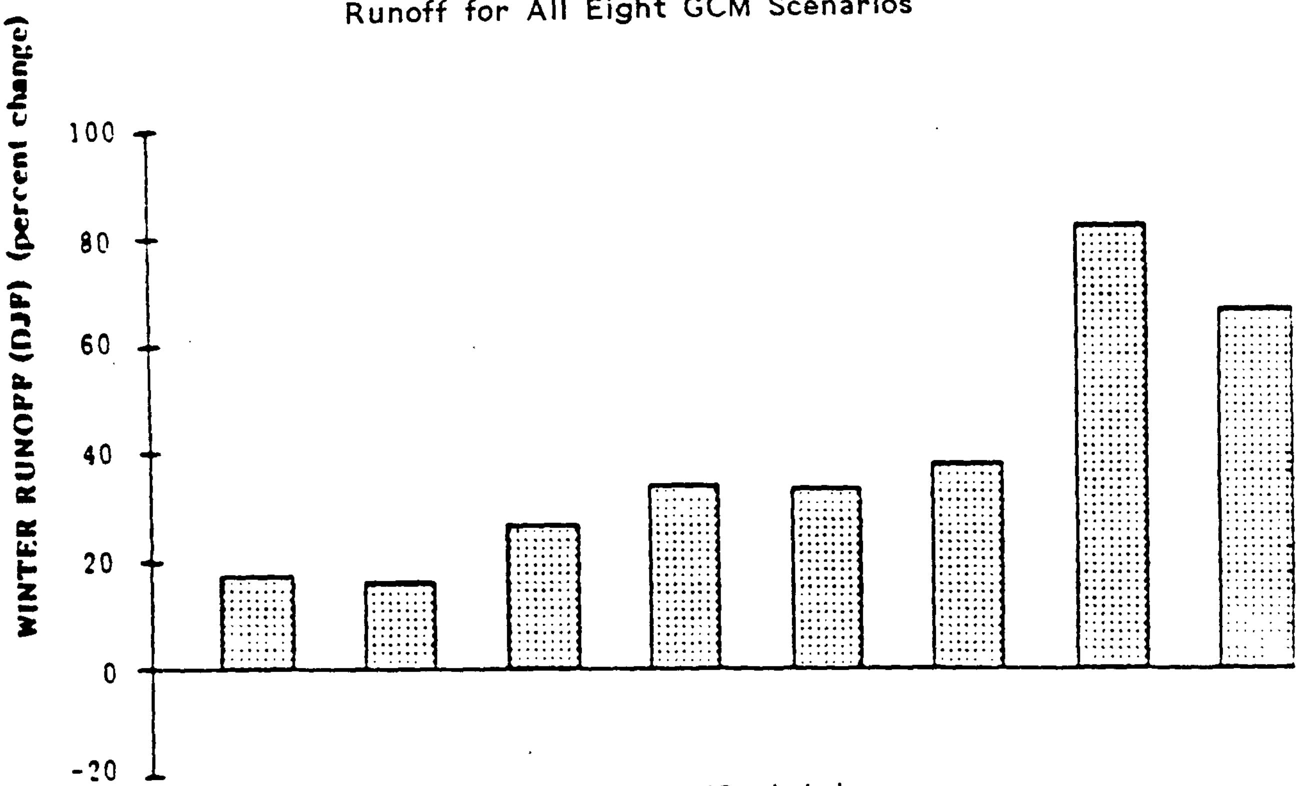


FIGURE IV-5b

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



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1. <u>The Inherent Accuracy of the Model</u>. Models vary in their ability to reproduce existing hydrologic conditions in a watershed. Obviously, models designed to investigate one small physical characteristic of a watershed may be less accurate and less applicable for climate impact assessment than a model that incorporates all the important hydrologic characteristics of a basin.

2. <u>Initial Model Calibration and Changing Conditions</u>. When first calibrating a model, assumptions are made about the initial values of input parameters, and model output is computed and compared with the actual behavior of the hydrologic system. If necessary, input parameters are then changed and the comparison repeated until the fit is considered to be satisfactory. The dependence of the model on its initial calibration has particular significance for those circumstances in which a climatic change significantly affects the underlying pre-defined parameters of a model. An example of this situation is the extent to which a climatic change might lead to a significant change in either the extent of vegetative cover or the hydrologic behavior of the existing cover. Under these conditions, the initial calibration of the model is no guarantee that the model can be used accurately for evaluating conditions following a climatic change. The most appropriate models, therefore, are those that can account for changes in the initial conditions and assumptions through the incorporation of deterministic, physically-based components, rather than mathematically-based parameterizations.

3. <u>The Availability of Input Data, Including Comparative Historical Data</u>. This factor plays a major role in verifying model capabilities. Historical hydrologic data must be available both to calibrate any given model and to evaluate the accuracy and applicability of a model to any given watershed. Unless a model can be verified using actual historical records, the use of a regional model to evaluate changes in climate will be questioned. Estimating the accuracy of any specific simulation is difficult in the absence of good records of existing conditions. Given such records, however, it is reasonably simple to compare observed data with model flows and to evaluate model accuracy.

4. <u>The Accuracy of the Input Data</u>. The quality of the input data is important for model verification and for the initial choice of model parameters. This point may be obvious to most hydrologists familiar with the varying quality of temperature and precipitation data, but should be kept in mind by climatologists and climate impact analysts: hydrologic measurements are frequently inaccurate or simply unavailable. As a result, care should be taken in the choice and application of data sets. Perhaps the most significant problems encountered in achieving a good fit are errors in input data or errors in the historical data used for model calibration. In these cases, adjusting input parameters to meet erroneous data will result in biases to subsequent model runs. This problem is not unique to hydrologic simulation -- almost all forms of modeling are limited by the quality of input or historical data. Modelers must be aware of these limitations when evaluating model accuracy and calibrating model parameters.

5. Model Flexibility, Ease of Use, and Adaptability. Modeling techniques designed for one hydrologic regime may not be directly applicable to different types of watersheds. Hydrologic characteristics in different watersheds are extremely variable in the timing, nature, and magnitude of flows. If any information that can be generalized for different types of watersheds is to be gained by regional impact assessment, assessment techniques must be applicable to many diverse watersheds and they must be flexible in their application.

6. Compatibility with Existing General Circulation Models. Finally, the need for compatibility with existing general circulation models arises from our desire to improve our understanding of the most likely impacts of anthropogenic climatic change. Since general circulation models (GCMs) now provide the most detailed information on future changes in climate, the ability to link regional hydrologic models with output from GCMs will improve our ability to understand the regional impacts of global climatic changes. GCMs do not yet provide sufficient detail on regional impacts to be used for purposes of prediction, but they do provide an internally-consistent description of plausible patterns of climatic change. By linking the two--GCMs and regional hydrologic models--we can develop methods that enhance the abilities of both. Furthermore, methods for assessing regional hydrologic impacts will improve with continued improvements both in the quality of GCM models and output data and in the flexibility and versatility of regional models.

F. FUTURE RESEARCH DIRECTIONS

Research in the field of hydrologic impacts of climatic changes has only begun to identify the nature of possible changes in water resources and far more work is needed in a number of important areas, ranging from improvements in large-scale climate models to the development of methods for evaluating the economic and social costs of changes in water availability and water quality. This section outlines a number of areas where substantial progress could be made to improve our understanding of both the nature and magnitude of possible impacts.

1. Improvements are Needed in Large-Scale Climate Models. The best information on the nature of plausible future climatic changes comes from a variety of large-scale models of the climate, including general circulation models. Unfortunately, these models have two major limitations that reduce their value to scientists interested in the regional hydrologic impacts of climatic changes: their parameterizations of hydrologic processes are greatly simplified compared to actual processes, and the computer time required to generate detailed information on regional (rather than global-averaged) impacts is too great. Improvements are needed in both of these areas if we are to be able to get a sense of the magnitude, and even the direction, of some of the most important regional impacts on water resources that will result from climatic changes over the next several decades. Furthermore, as regional and hydrologic predictive capabilities of GCMs improve, GCM data can be used to drive more accurate regional models in order to get better information on smaller-scale hydrologic impacts than is presently available.

2. Improvements are Needed in Regional Assessment Techniques. The importance of looking at the regional hydrologic impacts of climatic changes, rather than simple global averages, cannot be overemphasized. Quite simply, global averages hide considerable detail that is of crucial importance. For example, knowing that the global average increase in precipitation from a doubling of atmospheric carbon dioxide will be on the order of 5-10 percent is far less important than the information that soil moisture in agricultural regions may be significantly reduced during important parts of the growing season (Manabe and Wetherald 1986, Gleick 1986c), that the timing of runoff in regions sensitive to winter flooding may be shifted from spring to winter months due to changes in the extent and dynamics of snowfall and snowmelt (Gleick 1986c), or that lake levels may decrease (or increase) due to changes in evaporation and runoff rates (Cohen 1986). For these reasons, more work needs to be done on developing a variety of assessment methods that are suitable for addressing different types of regional hydrologic problems, in different types of hydrologic basins.

3. There Need to be More Assessments Specific Region. As new methods are developed, additional studies need to be done on specific regions whose water resources may be sensitive to changes in climate. As Gleick (1986c) points out for the Sacramento Basin in California, watersheds in which existing water resources are heavily subscribed will be vulnerable to changes in either the timing or magnitude of hydrologic changes. While arid regions often fall in this category, many watersheds in temporate and humid climates may also be vulnerable due to heavy industrial, commercial, or residential water use. An important task is to identify particularly sensitive watersheds and to begin to assess both plausible changes in water resources and the socioeconomic areas in which such changes would have particularly severe results.

4. Economic and Societal Impacts Changes in Water Resources. Despite the importance of understanding how water resources will be affected by changes in climatic conditions, the possible changes in water availability themselves are of less interest to society than the subsequent effects on human activities, such as changes in agricultural productivity, alterations in flood and drought probabilities, effects on water-resource management activities, and so on. Methods for converting hydrologic changes into economic and social costs must be very carefully developed and reviewed. Extreme caution must be used to do these assessments. Experience with risk assessment in other areas, such as the environmental costs of energy production and use (see, for example, the reviews by Holdren et al. 1979) have highlighted the numerous difficulties of identifying appropriate indicators of costs, the problems of "apples and oranges" comparisons, and a variety of other pitfalls and methodological problems that must be avoided. Novaky et al. (1985) and Cohen (1986) outline possible impact areas and methods, but considerably more theoretical work is needed before such assessments can be profitably attempted.

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V. EFFECTS ON HUMAN HEALTH

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A. FINDINGS

1. Weather has a profound effect on human health and well-being. It has been demonstrated that weather is associated with changes in birth rates, and sperm counts, with outbreaks of pneumonia, influenza and bronchitis, and is related to other morbidity effects linked to pollen concentrations and high pollution levels.

2. Large increases in mortality have occurred during previous heat and cold waves. It is estimated that 1,327 fatalities occurred in the United States as a result of the 1980 heat wave; the number occurring in Missouri alone accounted for over 25% of the total.

3. Hot weather extremes appear to have a more substantial impact on mortality than cold wave episodes. Most research indicates that mortality during extreme heat events varies with age, sex, and race. Factors associated with increased risk from heat exposure include alcoholism, living on higher floors of buildings, and the use of tranquilizers. Factors associated with decreased risk are use of air conditioning, frequent exercising, consumption of fluids, and living in shaded residences. Acclimatization may moderate the impact of successive heat waves over the short term.

4. Threshold temperatures for cities, which represent maximum and minimum temperatures associated with increases in total mortality, have been determined These threshold temperatures vary regionally; for example, the threshold temperature for winter mortality in mild southern cities such as Atlanta is 0°C and for more northerly cities, such as Philadelphia, it is -5°C.

5. Humidity has an important impact on mortality since it contributes to the body's ability to cool itself by evaporation of perspiration. It also has an important influence on morbidity in the winter because cold, dry air leads to excessive dehydration of nasal passages and the upper respiratory tract and increased chance of microbial and viral infection.

6. Precipitation in the form of rainfall and snow is also associated with changes in mortality. In New York City, upward trends in mortality were noted the day after snowfalls that had accumulated 2 inches or more. In Detroit where snow is more common, the snowfall accumulation exceeded 6 inches before mortality increases were noted.

7. If future global warming induced by increased concentrations of trace gases does occur, it has the potential to significantly affect human mortality. In one study, total summertime mortality in New York City is estimated to increase by over 3,200 deaths per year for a 7°F trace-gas-induced warming without acclimatization. If New Yorkers fully acclimatize, the number of additional deaths are estimated to be no different than today. It is hypothesized that, if climate warming occurs, some additional deaths are likely to occur because economic conditions and the basic infrastructure of the city will prohibit full acclimatization even if behavior changes.

8. Two areas of important future research include investigation of morbidity impacts and the costs to society of indirect impacts (e.g., costs associated with modifying living and working areas, decreases in productivity, and other climate/stress-induced impacts).

B. INTRODUCTION

There is a large body of literature devoted to the impact of variable climate on human well-being. Most of the research has been done by medical scientists, and a minor amount of the work has been performed by climatologists. This section will attempt to describe much of the relevant research that has been published to date. Topics will be subdivided on the basis of weather events, as many of the manuscripts evaluated employ a regression technique to determine the impacts of one or more climatic events on human health.

There appears to be general agreement that weather has a profound impact on human health, but scientists do not agree on the precise mechanisms involved. For example, some of the research suggests that extreme weather events appear to have the greatest influence on health. Driscoll (1971a) correlated daily mortality for 10 cities with weather conditions in January, April, July, and October and found that large diurnal variations in temperature, dewpoint, and pressure were associated with many high mortality days. In addition, hot, humid weather with concomitant high pollutant concentrations were also contributory mechanisms. Other studies do not attribute large variations in mortality to extreme events, but rather to the normal seasonal changes in weather (Persinger, 1980).

The importance of determining the role of weather in human health cannot be understated. Reports of large increases in mortality during heat and cold waves are commonplace; for example, the National Oceanic and Atmospheric Administration (NOAA) estimated that 1,327 fatalities in the United States were directly attributed to the 1980 heat wave; fatalities in Missouri alone accounted for over 25% of the total excess deaths (U.S. Department of Commerce, 1980). During a heat wave in 1963, more than 4,600 deaths above a computed mean occurred in June and July in the eastern United States (Schuman et al., 1964). The impact of weather on human well-being goes beyond mortality; even birth rates and sperm counts appear to be affected by meteorological phenomena (Calot and Blayo, 1982; Tjoa et al., 1982; White, 1985).

This report will concentrate on the effects of weather upon human mortality. However, there are numerous other impacts of weather on the general health of the population, including morbidity, short-term changes in mood, emotional well-being, and aberrations from normal behavior. For example, asthma attacks, many of which occur from inhalation of airborne agents such as spores and molds, appear to be related to various meteorological variables (White, 1985). Goldstein (1980) found that clusters of attacks are preceded by the passage of a cold front followed by a high pressure system. Morbidity attributed to pneumonia, influenza, bronchitis, and probably many other illnesses is also weather-related (White, 1985).

In addition, several atmospheric phenomena that are indirectly related to weather and might have an impact on mortality (the most notable being atmospheric pollutants and pollen concentrations) are not included in this review. A partial annotated bibliography of pollen concentration is presently available (Kalkstein and Robeson, 1984), but there is little research comparing weather/pollen relationships to human health. Meteorologic conditions exert a large influence on pollution concentrations and dispersion and they also affect the impact of pollution on mortality and morbidity. Much of the literature on this topic has already been summarized (Stern, 1977).

Probably the most intensively-studied weather element that affects human mortality is air temperature, especially the impact of summer heat. A detailed description of temperature/mortality relationships follows.

C. TEMPERATURE EFFECTS

1. General Impacts

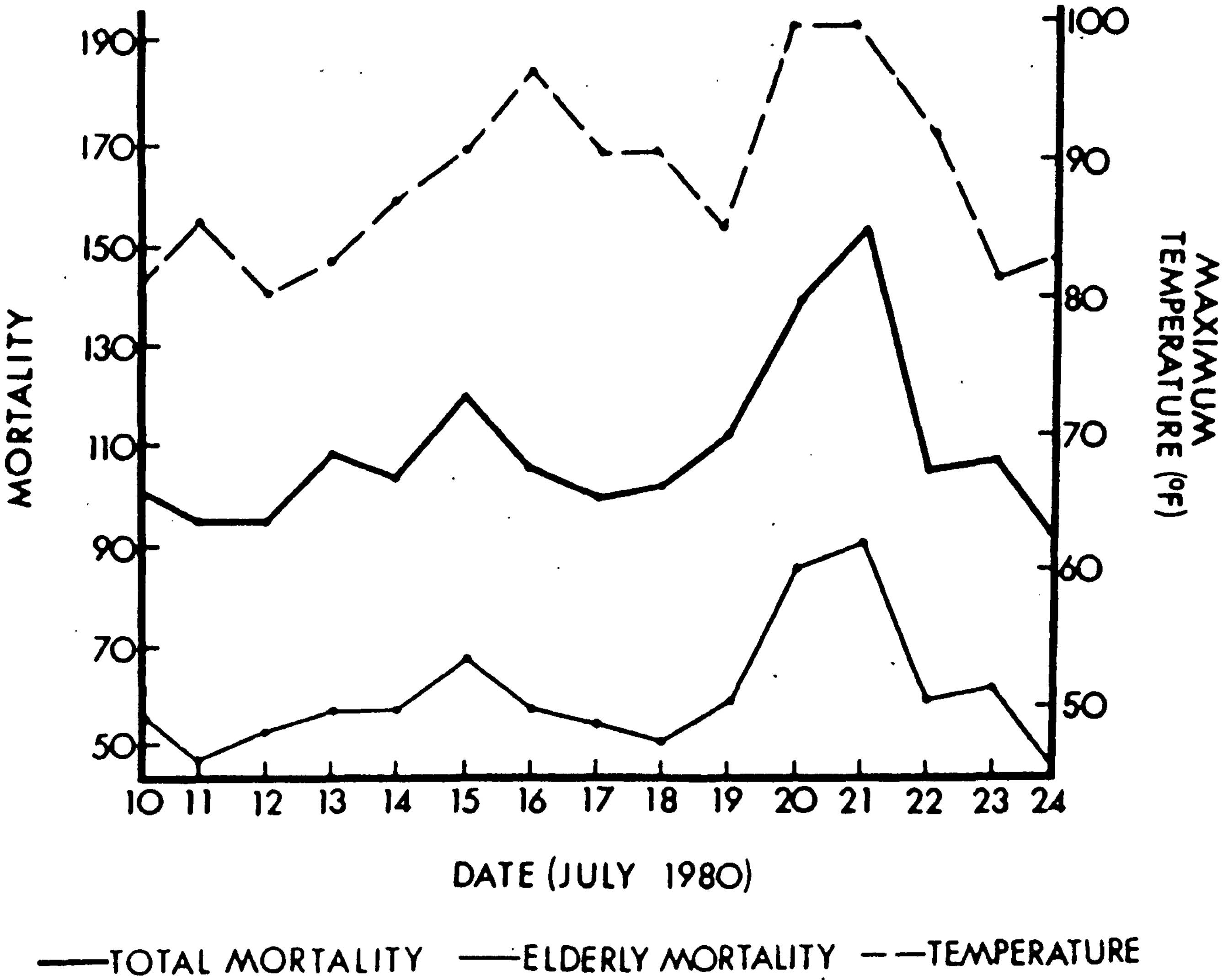
The impact of temperature on morbidity and mortality can be assessed at both the seasonal and daily level. The variability in occurrence of numerous illnesses is linked to somewhat predictable seasonal trends in temperature (Persinger, 1980), although significant year-to-year differences do occur. Medical disorders such as bronchitis, peptic ulcer, adrenal ulcer, glaucoma, goiter, eczema, and herpes zoster are related to seasonal variations in temperature (Tromp, 1963). Heart failure (most often myocardial infarction) and cerebrovascular accidents represent two general mortality categories that have been correlated many times with ambient monthly temperatures (Persinger, 1980). Complications from these disorders can be expected at higher temperatures since the body responds to thermal stress by forcing blood into peripheral areas to promote heat loss through the skin. This increases central blood pressure and encourages constriction of blood vessels near the core of the body. However, increases in heart disease are also noted at very cold temperatures as well. Strong negative correlations have been found between winter temperature and deaths in certain North American, northern Asian, and European countries (Persinger, 1980).

The degree of seasonality in the climate of a region also appears to affect mortality rates. Katayama and Momiyama-Sakamoto (1970) reported that countries with smaller seasonal temperature ranges exhibit steeper regression lines in temperature-mortality correlations than do countries with greater temperature ranges. Maximum death rates in warmer countries are found at below normal temperatures, and in cooler countries similar temperatures will produce no appreciable rise in mortality.

There is conflicting evidence concerning the impact of daily temperature fluctuations on human mortality. Some studies contend that mostly long-term (i.e., monthly and annual) fluctuations in temperature affect mortality (Sakamoto and Katayama, 1971) and only small, irregular aberrations can be explained by daily temperature variability (Persinger, 1980). However, Kalkstein and Davis (1985) report that daily fluctuations in temperature can increase mortality rates by up to 50% in certain cities. This has been corroborated in a detailed study of New York City mortality where large increases in total and elderly mortality occurred during the 1980 heat wave (Figure V-1).

FIGURE V-1

Mortality During 1980 Heat Wave in New York City



Source: Kalksten, Davis and Skindlow (September 1986).

2. Impacts of Hot Weather

a. General Relationships

Much of the temperature-mortality research has concentrated on heat and cold wave episodes. It appears that hot weather extremes have a more substantial impact than cold, and many "heat stress" indices have been developed to assess the degree of impact (Quayle and Doehring, 1981; Kalkstein, 1982; Steadman, 1984). Driscoll (1971b) related 19 different meteorological variables with total mortality and other more specific mortality classes (cause of death, age) and identified high temperature as the most important causal mechanism in summer. Many other studies support this relationship between temperature and mortality (Ellis, 1972; Ellis et al., 1975; Oechsli and Buechley, 1970). Interestingly, a majority of studies have found that most of the excess deaths that occurred during periods of intense heat were not attributed to causes traditionally considered to be weather-related, such as heat stroke (Gover, 1938). Consequently, many researchers continue to utilize total mortality figures in their analyses, as deaths from a surprisingly large number of causes appear to escalate with increasing temperature (Applegate et al., 1981; Jones et al. 1982).

Although most researchers have preferred the use of maximum temperature as the primary predictor of mortality, others continue to utilize average daily temperature as their primary weather statistic. While Kutschenreuter (1959) found that maximum temperature with a 1-day lag was the single most important predictive weather/mortality variable, Rogot (1973) worked strictly with daily average temperature to evaluate cardiovascular diseases; others have even used weekly averages (Lye and Kamal, 1977; Callis and LeDuc, 1985). Those who use daily averages cite the importance of warm nights in contributing to mortality, something that is neglected when utilizing maximum temperatures alone (Ellis et al., 1975). However, others report that daily averages tend to mask the effect on mortality of large daily oscillations in temperature (MacFarlane and Waller, 1976).

A number of studies compare death rates for extreme periods with those encountered during normal meteorological periods; this approach has met with some success (Oechsli and Buechley, 1970; Schuman et al., 1964; Schuman, 1972). Jones et al. (1982), in summarizing the work of others, found that high temperature, the number of days that the temperature is elevated, high humidity, and low wind velocity are all found within the climate/mortality models of various researchers (Figures V-2 and V-3). An earlier work by Schuman (1972) includes smog as a related mechanism associated with fluctuations in death rate (Figure V-4).

Rather than incorporating daily death totals, many heat wave/mortality studies have utilized weekly mortality totals compiled by the Centers for Disease Control for their primary input (Centers for Disease Control, 1984). Schuman (1972) calculated expected weekly death rates based on a 5-year moving mean, and periods of weekly excess mortality were isolated. Callis and LeDuc (1985) compared weekly mortality rates to weather for 10 U.S. cities and uncovered some large weather-induced fluctuations. In general, studies

FIGURE V-2

Deaths, by Date of Occurrence, Kansas City, MO, Residents
June 1978 to July 1979 and 1980

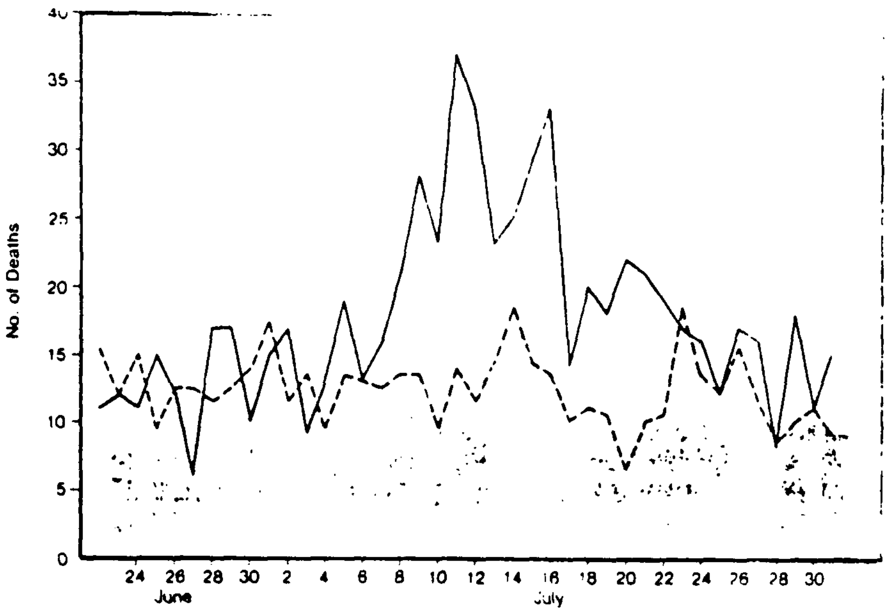
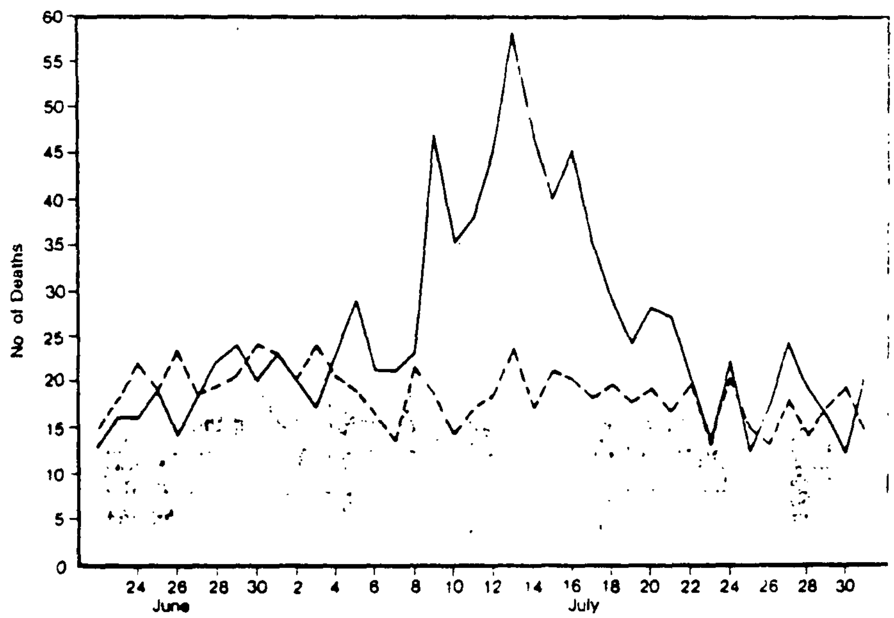


FIGURE V-3

Deaths, by Date of Occurrence, St. Louis, MO, Residents
June 1978 to July 1979 and 1980

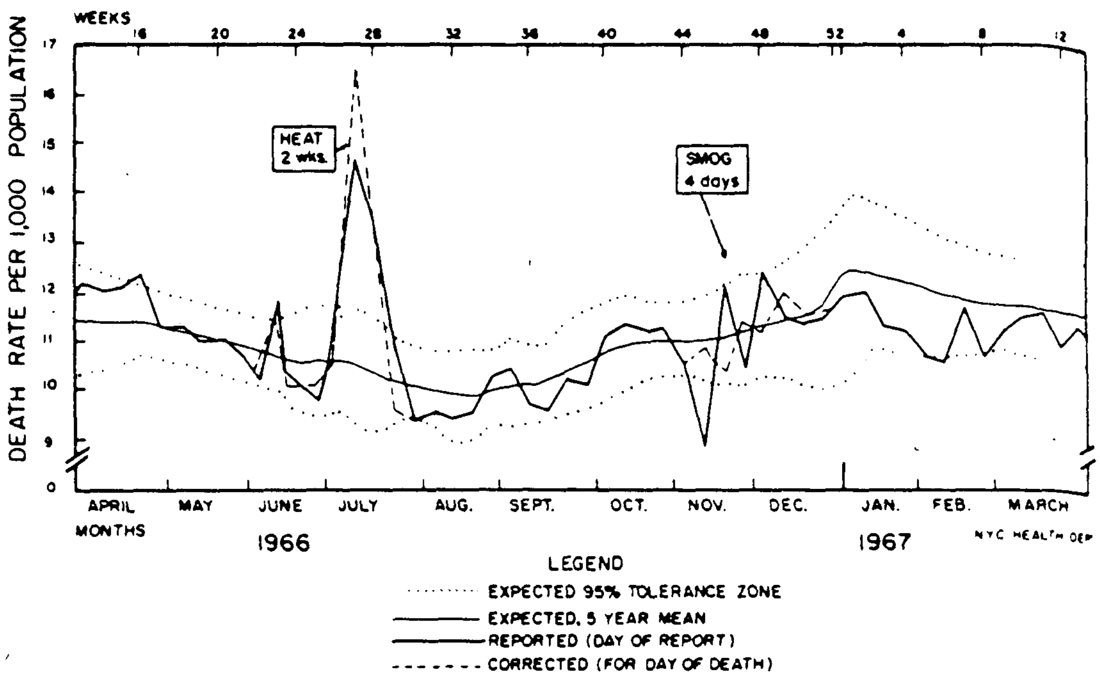


Dotted line indicates mean values for 1978 to 1979 period; solid line, 1980.

Source: Jones 1980.

FIGURE V-4

Fluctuations in Death Rate in New York Associated with Episodes of Heat (July 2-15) and Smog (November 23-26) in 1966 -- Illustrating the Method of Excess Mortality



Source: Shuman, S.H., 1972: "Patterns of Urban Heatwave Deaths and Implications for Prevention: Data From New York and St. Louis during July 1966." Environmental Research 5, 62.

incorporating weekly data sets are less revealing than their daily counterparts, as extreme episodes are often dampened when time scales are increased.

One of the most commonly reported findings in heat wave-mortality studies involves the lag time between the temperature event and the mortality response. A lag period of one day was most often uncovered (Ellis, 1972; Ellis et. al., 1975; Ellis and Nelson, 1978); others, however, have observed a two- to three-day lag (Schuman, 1972; Oechsli and Buechley, 1970), and some have noted no lag (Kalkstein and Davis, 1985).

Temperature affects not only mortality, but also morbidity. Applegate et al. (1981) demonstrated the relationship between temperature and morbidity. In that study, as shown in Figures V-5 and V-6, he found that emergency room hospital visits and admissions appear to be correlated with the 1980 heat wave in Tennessee.

b. Responses of the Population

Kilbourne et al. (1982) conducted a case study in which a number of heat factors associated with heat stroke were identified. Factors found to be associated with an increased risk of heat stroke included alcoholism, living on higher floors of buildings, and the use of tranquilizers. Factors found to be associated with a decreased risk were use of air conditioning, frequent exercising, consumption of fluids, and living in a well-shaded residence. During extreme heat episodes, heat stroke risk is increased as demonstrated by the 1980 heat wave in St. Louis, which resulted in a ten-fold increase in total deaths (Figure V-7).

Most research indicates that mortality rates during extreme heat vary with age, sex, and race. Oechsli and Buechley (1970) found that mortality rates during heat waves increase with age. This is supported by the work of others (e.g., Bridger et al., 1976, Lye and Kamal, 1977; Jones et al., 1982). The elderly seem to suffer from impaired physiological responses and often are unable to increase their cardiac output sufficiently during extremely hot weather (Sprung, 1979). In addition, sweating efficiency decreases with advancing age (Crowe and Moore, 1973), and many of the medications commonly taken by the elderly have been reported to increase the risk of heat stroke (Jones et al., 1982). Certain researchers have determined slight rises in mortality rates of infants during heat waves (Bridger et al., 1976; Ellis, 1972; Foster et al. 1968), but this is not a universal finding (Schuman, 1972).

Studies relating mortality to gender also yield conflicting results. Studies in which increased mortality rates were found among females during hot weather include those of Applegate et al. (1981) and Rogot and Padgett (1976). Rotton (1983) suggests that this may be attributed to differences in dress among the sexes. Bridger et al. (1976) and Ellis (1972) found higher heat-induced mortality rates among men. Studies of the role of race have also produced conflicting results. Schuman (1972) found that blacks appear more susceptible to heat-related deaths in St. Louis and whites are more

FIGURE V-5

Daily Heat-Related Emergency Room Visits, Hospital Admissions, and Total Deaths, June 25-July 30, 1980 -- Shelby County, Tennessee

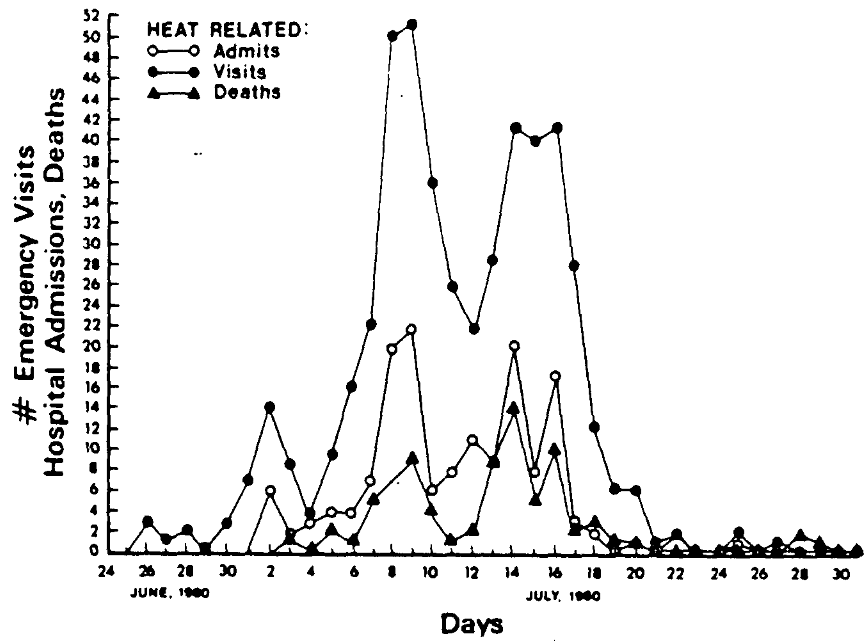
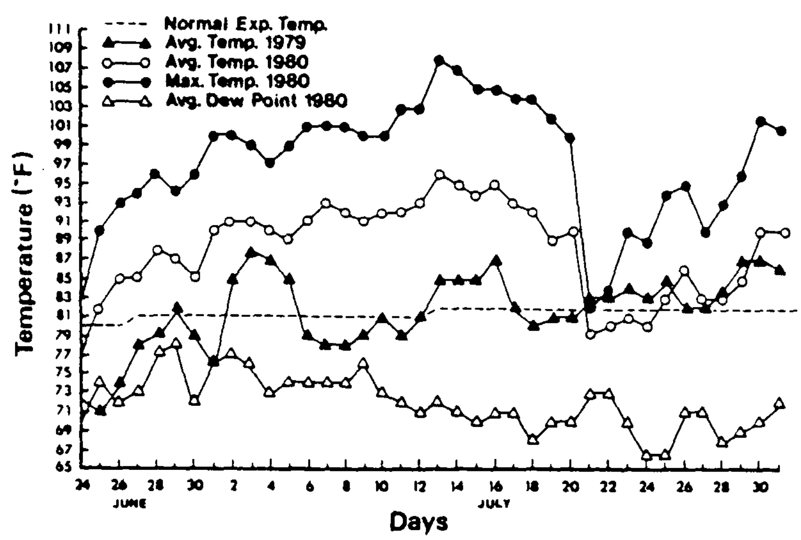


FIGURE V-6

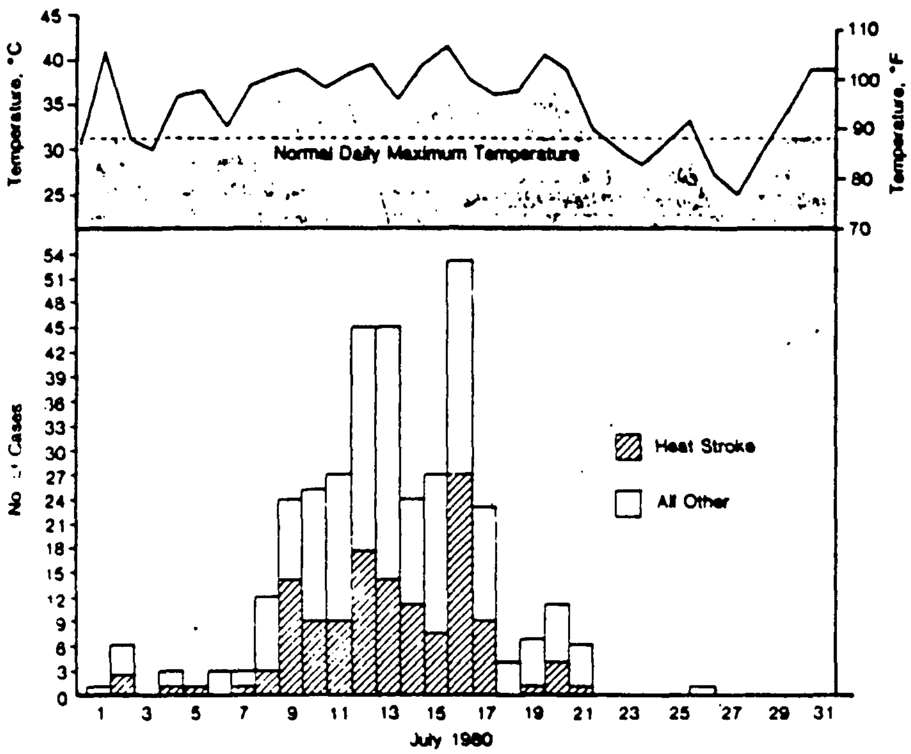
Daily Temperatures, June and July 1979 Versus June and July 1980, and Dew Points for 1980 -- Shelby County, Tennessee



Source: Applegate, W.B., MD, MPH; J.W. Runyan, Jr., MD; L. Brasfield, MS; M.L. Williams, MSW; C. Konigsberg, MD, MPH; and C. Fouche, RRA, 1981: Analysis of the 1980 heat wave in Memphis. Journal of the American Geriatrics Society, 29,338-29,339.

FIGURE V-7

Heat-Related Illness by Date of Onset and Daily Maximum Temperatures
St. Louis, MO, July 1980



Source: Jones, T.S., MD, MPH; A.P. Liang, MD, MPH; E.M. Kilbourne, MD; M.R. Griffin, MD; P.A. Patriarca, MD; S.G.G. Wassilak, MD; R.J. Mullan, MD; R.F. Herrick, MS; H.D. Donnel, Jr., MD, MPH; K. Choi, PhD; and S.B. Thacker, MD; 1982: Morbidity and mortality associated with the July 1980 heat wave in St. Louis and Kansas City, MO. Journal of the American Medical Association, 247, 3327-3330.

susceptible in New York (Table V-1). However, Ellis et al. (1975) and Bridger et al. (1976) have discovered that white mortality rates are higher than black's under all examined conditions. Rather than race, socioeconomic status may have an influence on weather/mortality relationships. Large numbers of deaths during heat waves are found among poor inner-city residents who have little access to cooler environments (Jones et al., 1982).

Initial observations of daily standardized deaths vs. maximum temperature suggest that weather has an impact on only the warmest 10-20% of the days; however, the relationship on those very warm days is impressive (see Figure V-8). During warm periods, 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 sums of squares technique (Kalkstein, 1986). The threshold temperature for deaths in New York, above which mortality increases dramatically, is 92°F. This procedure can be repeated for winter, as discussed later in this section, where the threshold temperature represents the minimum temperature below which mortality increases.

c. Acclimatization

Several studies have evaluated acclimatization as a factor contributing to heat-related deaths. Gover (1938) reported that excess mortality during a second heat wave in any year will be slight in comparison to excess mortality during the first, even if the second heat wave is unusually extreme. Two possible explanations for this phenomenon are provided. First, the weak and susceptible members of the population die in the early heat waves of summer, thus lowering the population of susceptible people who would have died during subsequent heat waves. Second, those who survive early heat waves become physiologically acclimatized and hence deal more effectively with later heat waves (Marmor, 1975). Rotton (1983) suggests that geographical acclimatization is also significant, and people moving from a cool to a subtropical climate will adapt rather quickly, often within two weeks. However, the population must still make behavioral and cultural adjustments (Ellis, 1972). Further support for geographical acclimatization is provided by Kalkstein and Davis (1985), who noted that mortality increased dramatically during heat waves in northern cities but not in southern cities.

There is some research that implies that the effect of acclimatization has been overstated by many scientists. The use of the wind-chill index in winter and the temperature-humidity index in summer by many meteorologists seems to indicate that they believe acclimatization may have minimal impact on human activities. Both indices are based on absolute values only: a temperature of 93°F with a humidity of 43% yields the same temperature-humidity index value whether it occurs in New Orleans or Duluth. The hot weather indices most widely-accepted by the National Weather Service are all absolute, and they include the temperature-humidity index, humiture, humidex, the discomfort index, and apparent temperature (Thom, 1959; Winterling, 1979; Steadman, 1979a; 1979b; Weiss, 1983). The only geographically relative index that has been published, the weather stress index, is only beginning to be utilized to evaluate a variety of the impacts that climate has on humans (e.g., mortality) (Kalkstein and Valimont, 1986).

TABLE V-1

Comparison of Patterns of Heat-Wave Mortality in in New York and St. Louis (July 1966)

Characteristic	New York	St. Louis
Population at risk (approximately)	7.8 million	728,000
Duration of heat wave	14 days	28 days
No. days over 90°F	12	24
Mortality		
Excess deaths (estimated number) a/	1181	618
All ages (proportion rise)	36.3%	55.8%
65+ years (proportion rise)	52.6%	81.1%
"Rate" per million per week	75.7%	197.1
Race		
White	39%	41%
Nonwhite	20%	119%
Sex		
Male	25.3%	28.0%
Female	50.4%	57.5%
Race-sex group at highest risk b/	WF 56.2%	NWF 140.1%
Range of excess deaths by residence (census tract)	10% to 140%	-18% to 260%

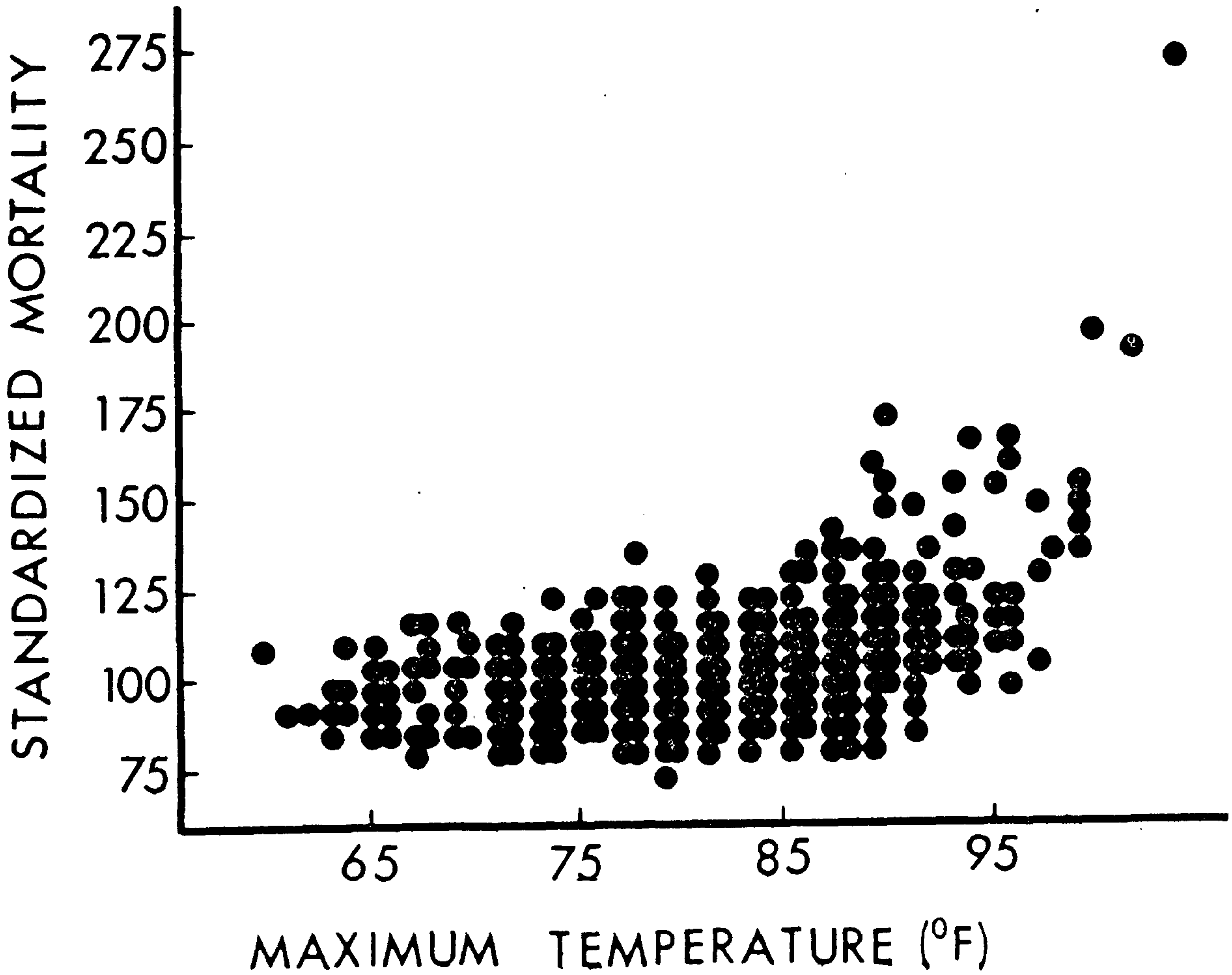
a/ Applying the method of excess mortality to an arbitrary control period (see text): For New York--2 weeks of "average" mortality during May 7-20, 1966; for St. Louis--4 weeks of mortality during July of 1965 (7/2-7/29).

b/ WF = white female, NWF = nonwhite female.

Source: Schuman, S. H., 1972: Patterns of urban heat wave deaths and implications for prevention: Data from New York and St. Louis during July, 1966. Environmental Research, 5, 58-75.

FIGURE V-8

Daily Summer-Season Standarized Mortality Versus
Maximum Temperature: New York



Source: Kalkstein, L.S., R.E. Davis, J.A. Skindlov, and K.M. Valimont. The impact of human-induced climatic warming upon human mortality: A New York City case study. Proceedings of the International Conference on Health and Environmental Effects of Ozone Modification and Climate Change, in press.

One cultural adjustment that may have an impact on heat wave-related mortality is the use of air conditioning. Kilbourne et al. (1982), in an attempt to identify factors related to heat stroke, found a strong negative relationship between daily hours of home air conditioning and heat-related mortality. This finding is supported by Oechsli and Buechley (1970) in their study of heat-related deaths in Los Angeles. However, Ellis and Nelson (1978) have noted that during the past 30 years, mortality during heat waves in New York City has not changed significantly despite the increased use of air conditioning. Analysis by Marmor (1975) supports this finding; his study covering a 22-year period implied that air conditioning may be decreasing excess mortality during initial summer hot spells only.

d. Some Predictive Equations

Several general algorithms have been developed to predict mortality changes during heat waves. Buechley et al. (1972) developed the following algorithm for heat-related mortality at temperatures above 90°F:

$$TMR = cycle + 0.10e^{0.2(F^{1}-90)} \quad (1)$$

where TMR is the temperature-specific mortality ratio (the predicted mortality for the day divided by the average annual daily mortality), cycle is the expected mortality ratio for that day of the year (an attempt to account for the impact of seasonality on mortality), and F^1 is yesterday's temperature. Cycle is computed from several years of mortality data and varies in a sinusoidal fashion, peaking in the winter and reaching a minimum at the end of the summer. Each day has a distinctive cycle value depending upon the mean mortality rate for that time of year. The following example represents a hypothetical calculation of TMR. Assume that the maximum temperature on a given day is 100°F, and the cycle is 0.95. $TMR = 0.95 + 0.1e^{0.2(100-90)}$, which equals 1.70. Thus the equation predicts that mortality on the day following the 100° maximum temperature will equal 170% of the annual mean daily mortality. Oechsli and Buechley (1970) had previously developed a related algorithm, the age- and temperature-specific mortality ratio model (ATMR):

$$ATMR = 98.806 + e^{(-15.23 + .0385\ Age + .1655\ F)} \quad (2)$$

where F is the present day's maximum temperature.

In a more recent study, Marmor (1975) attempted to develop a model that accounted for acclimatization effects. This led to his sensitivity index, which decreased as the population was exposed to more hot days during the season. Sensitivity (S^d) equals:

$$1/(1 + e^{(A_d - 6)/0.46}) \quad (3)$$

where A_d is the total number of previous days with temperatures over 90°F.

This sensitivity value was added to a newer version of the TMR algorithm, producing the following:

$$TMR = cycle + (0.05 + 0.06\ sensitivity)\ e^{(F^1-90)0.2} + 0.05e^{(F-90)0.2} + 0.07\ e^{(f-75)0.2} \quad (4)$$

where f is the previous day's minimum temperature, F^1 is the previous day's maximum temperature, and F is the present day's maximum temperature (Marmor 1975).

3. Impact of Cold Weather

a. General Relationships

Many studies have provided evidence that mortality rates increase during periods of cold weather. In general, total mortality is about 15% higher on an average winter day than on an average summer day (National Center for Health Statistics, 1978). However, increases in mortality during exceedingly cold periods are less dramatic than their hot weather counterparts (Kalkstein, 1984). The impact of cold on human well-being is highly variable. Not only is cold weather responsible for direct causes of death such as hypothermia, influenza, and pneumonia, it is also a factor in a number of indirect ways. Death and injury from falls, accidents, carbon monoxide poisoning, and house fires are all partially attributable to cold (U.S. Department of Commerce, 1984).

Hypothermia occurs when the core body temperature falls below 35°C (Centers for Disease Control, 1982). Certain sectors of the population appear more susceptible to hypothermia than others. Most victims fall in one or more of the following categories: the elderly, newborns, the unconscious, alcoholics, and people on medications (Fitzgerald and Jessop, 1982; Lewin et al., 1981; Hudson and Conn, 1974; Bristow et al., 1977; Massachusetts General Hospital, 1982). In addition, malnourishment, inadequate housing, and high blood ethanol levels increase the incidence of hypothermia (Centers for Disease Control, 1982).

Sex and race appear to be related to susceptibility to hypothermia. Nonwhite elderly men generally constitute the highest risk group, while white women comprise the lowest risk group (Rango, 1984; Centers for Disease Control, 1982). Women possess a higher skin temperature to core temperature gradient, suggesting that they are better able to maintain a higher body core temperature during periods of cold stress (Cunningham et al., 1978; Hardy and DuBois, 1940; Wyndham et al., 1964; Graham, 1983). Some studies contend that the difference in the response of men and women to cold is related to the amount of subcutaneous fat within the body (Hardy and DuBois, 1940; Wyndham et al., 1964), but other studies have failed to confirm this hypothesis (Bernstein et al., 1956; Gallow et al., 1984; Veicsteinas et al., 1982). Although women are less susceptible to hypothermia, they appear to be more susceptible to peripheral cold injuries such as frostbite (Graham and Lougheed, 1985).

Age appears to have an even greater impact upon hypothermia sensitivity than gender, and the elderly display the highest mortality rates of all groups. Vasoconstriction and shivering, two primary cold adaptive measures, appear to be reduced in many elderly persons (Collins et al. 1977; Collins and Easton et al. 1981; ; Wagner et al., 1974). In addition, many of the elderly do not discriminate changes in temperature well and are thus less able to adjust to them (Collins and Exton-Smith et al., 1981).

One of the first efforts to predict the impact of a severe cold wave was published by NOAA using algorithms developed by Kalkstein. Seven cities in the eastern and southern United States exhibited significant relationships between winter weather and mortality, and the following regression equations were developed for each:

Atlanta: MORT = C - .11 MT
Chicago: MORT = C - .08 MT
Cincinnati: MORT = C - .21 MT - .01 CDH + .13 HRS
Dallas: MORT = C - .12 MT - .13 MIN - .02 CDH
Detroit: MORT = C - .11 MT
Oklahoma City: MORT = C - .16 MT
Philadelphia: MORT = C + .09 MD + .01 CDH + .06 WAM - .08 WPM,

where MORT is the daily standard deviation increase in mortality above the mean, C is a constant (different for each city), MT is daily maximum temperature, HRS is the total hours in the day with temperatures below 32°F, MIN is daily minimum temperature, MD is daily minimum dewpoint, WAM is 3AM windspeed, WPM is 3PM windspeed, and CDH is a measure of the day's coldness and is calculated as follows:

$$CDH = \sum_{i=1}^{N} (32-5), \text{ where } T \leq 32.$$

T represents the hourly temperature and N represents total hours in a day with temperatures below 32°F. A map (Figure V-9) of predicted mortality increases during the January 1985 cold wave showed potentially significant increases in the eastern and central United States. Data limitations have precluded these predictions from being verified to date.

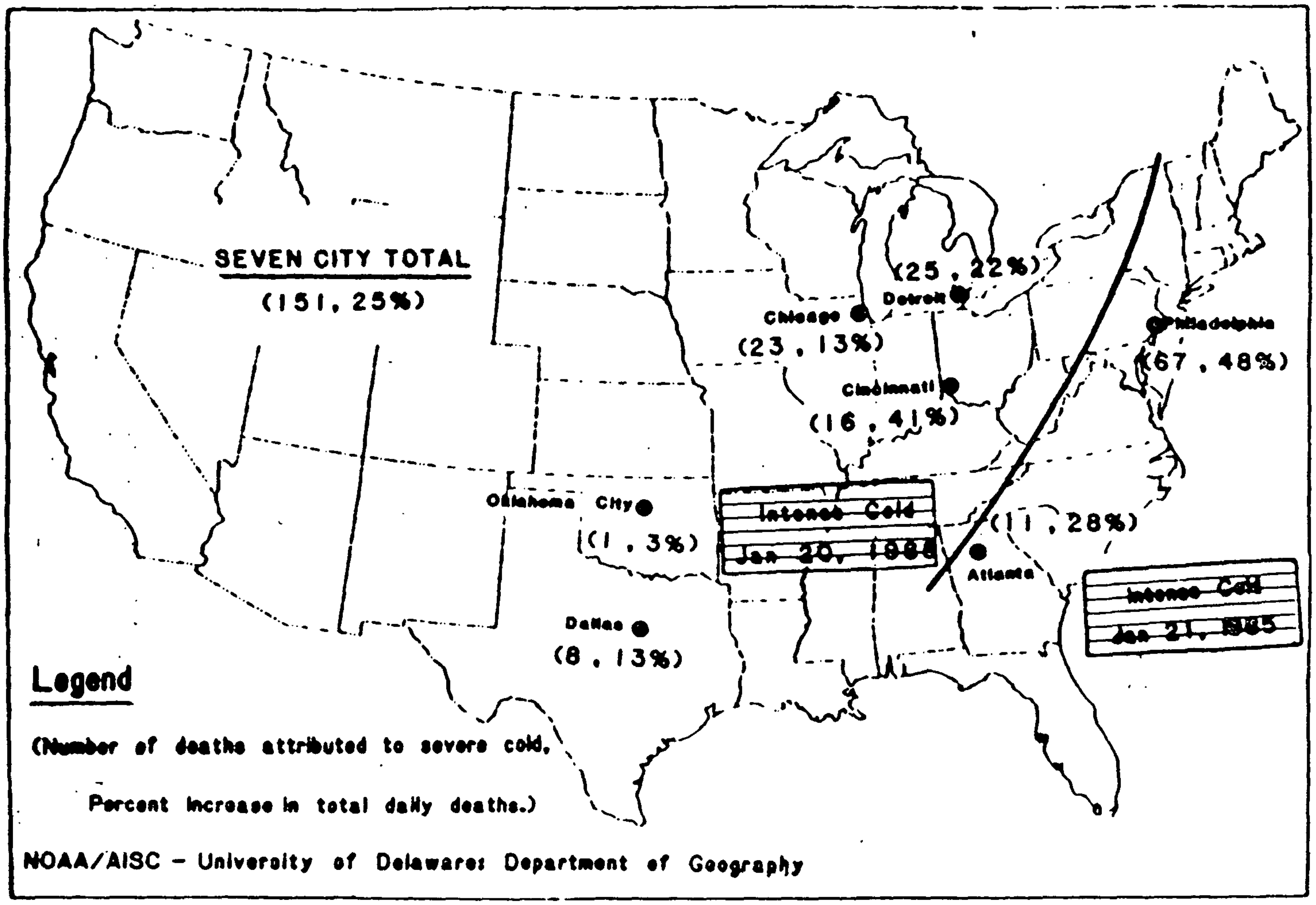
b. Adaptation

It appears that adaptation to cold temperatures can occur through repeated exposures. Radomski and Boutelier (1982) noted that men who had bathed in 15°C water for one-half hour over nine consecutive days before a trip to the Arctic showed less signs of cold-induced stress than non-treated men.

There appears to be a cold-adaptive mechanism influencing mortality as well. In a study comparing winter mortality rates for 13 cities in different climates around the U.S., a large differential response was noted. The southern cities seemed to exhibit the greatest increases in mortality during cold weather, while little or no response was found in northern cities

FIGURE V-9

Predicted Impact of the January 20-21, 1985, Intense Cold on Mortality



Source: Kalkstein, L.S., 1984: The impact of winter weather on human mortality. Climate Impact Assessment: United States, December, 21-23.

(Kalkstein, 1984). In a city such as Minneapolis, no increase in mortality was noted at temperatures down to -40°C, but in Atlanta, mortality increases were evident if the maximum temperature did not exceed 0°C (Kalkstein and Davis, 1985). Of the 13 cities studied, 7 demonstrated a statistically significant relationship between winter cold and mortality. The six non-significant cities included cold weather locations (Minneapolis) and mild West Coast locations where very cold weather is virtually unknown (Los Angeles and San Francisco). "Threshold temperatures," which represent temperatures below which notable increases in mortality occur, were established for the seven cities (Kalkstein and Davis, 1985). The threshold temperatures were comparatively mild for the more southerly cities (0°C for Atlanta; 1°C for Dallas) and somewhat colder for the more northerly cities (-5°C for Philadelphia). This differential geographical response seems to add credence to the importance of relative, rather than absolute weather conditions.

There is evidence that a lag time of two to three days exists between the offending cold weather and the ultimate mortality response (Kalkstein, 1984). Deaths did not necessarily rise on the day of the coldest temperatures, but in many cases, the sharpest increases were noted three days after the coldest weather occurred. A similar lag time was not noted after extremely hot summer days; the impact appears more immediate in summer.

D. HUMIDITY AND PRECIPITATION EFFECTS

1. Effects of Humidity

Humidity has an important impact on mortality since it influences the body's ability to cool itself by means of evaporation of perspiration. In addition, humidity affects human comfort, and the perceived temperature by humans is largely dependent upon atmospheric moisture content (Persinger, 1980).

The effects of low humidity can be especially dramatic in winter, when low moisture content induces stress upon the nasal-pharynx and trachea. When very cold, dry air passes through these organs, warming occurs and air temperatures in the pharynx can reach 30°F. The ability of this warmer air to hold moisture increases dramatically, and moisture is extracted at a prodigious rate from the nasal passages and upper respiratory tract, leading to excessive dehydration of these organs (Richards and Marriott, 1974). This appears to increase the chance of microbial or viral infection since a rise in the viscosity of bronchial mucous seems to reduce the ability of the body to fight offending microorganisms that may enter the body from the atmosphere. This may explain why Green (1966) found negative correlations between relative humidity and winter absenteeism in a number of Canadian schools.

In the summer, high moisture content during hot periods can lessen the body's ability to evaporate perspiration, possibly leading to heat stress. Recent weather/mortality models developed for the National Oceanic and Atmospheric Administration indicate that dewpoint temperature is directly related to mortality in several eastern cities when temperatures are very hot (Kalkstein, 1985). Another summer study indicated that mental well-being may also be influenced by summer relative humidity. Persinger (1975) found significant negative relationships between relative humidity and "mood scores," which represent a measure of happiness. Sanders and Brizzolara (1982) found relative humidity to be significantly related to a linear combination of three mood variables (vigor: $r = -.82$; social affection: $r = -.76$; elation: $r = -.56$).

2. Effects of Precipitation

Most of the precipitation/mortality research to date has concentrated on the impact of snow and other forms of severe winter weather. Rogot and Padgett (1976) found cold weather and snow to be statistically related to deaths from stroke and heart attack--a finding that has been corroborated by others. In a 1978 blizzard in Rhode Island, emergency room admissions for myocardial infarction rose markedly three days after the storm, and mortality from ischemic heart disease showed a large increase for a five-day period after the storm (Faiche and Rose, 1979). The authors attributed this rise to an increase in physical and psychological stress imposed by the storm. Glass and Zack (1979) concur, suggesting that an eight-day increase in deaths from ischemic heart disease following a number of blizzards was most likely a function of after-storm activities (snow shoveling, car pushing, etc.). Interestingly, these particular death increases appeared unrelated to temperature. Males appear to be at higher risk during these storms, probably due to the greater likelihood that they will be performing more vigorous physical activity after the storm (Glass and Zack, 1979).

In an ongoing study on the effects of snow accumulation in five U.S. cities, Kalkstein (1986) has determined threshold values of accumulated snow above which mortality rates appear to rise. In New York, significant upward trends in mortality were noted the day after snowfalls if two or more inches of snow had accumulated. In Detroit, where snow is more common, the snowfall accumulation exceeded six inches before mortality increases were noted. No significant relationship between snowfall accumulation and mortality was apparent in Chicago. Anderson and Rochard (1979) found increases in deaths from ischemic heart disease on, and for three days after, a four-inch or greater snowfall in Toronto. Major peaks in cardiovascular deaths in Minneapolis-St. Paul also appeared to follow days with heavy snows, with the rise most rapid the day after the storm (Baker Blocker, 1982).

Summer rainfall appears to have a limited impact on mortality. Kalkstein (1986) has shown that a significant decline in mortality is experienced the day after summer precipitation events in all of five U.S. cities studied (New York, Philadelphia, Chicago, Atlanta, Detroit). The precipitation event itself might have an indirect impact, as the cooler temperatures coinciding with a summer rainfall provide relief from excessively warm weather. However, in certain specific cases, rainfall might induce increases in mortality. Mack (1985) found that fatal automobile accidents increased in frequency during very light rain episodes (less than .01 inch) and heavy rainfalls (greater than 0.1 inch per hour).

E. FRONTAL PASSAGES, SUNSHINE, AND CLOUD COVER IMPACTS

Frontal passages may have a profound impact on well-being and mortality as large variations in weather conditions can occur in a very short time. Rapid changes in temperature have been shown to produce a number of physiological changes in the body. Rapid drops may affect blood pH, blood pressure, urination volume, and tissue permeability (Persinger, 1980). Outbreaks of epidemics may also be related to frontal passage. In his study of 59 years of data, Donle (1975) noticed sudden large increases in influenza outbreaks in Germany, Norway, and Switzerland often followed the passage of a surface trough. In general, these outbreaks occurred simultaneously with the influx of cold air over northern and western Europe (the passage of a surface wave is often followed by a rapid influx of cold air). The influenza outbreaks in Europe most frequently occurred between January and March, when cold air masses most commonly intruded over the area.

A number of studies have also found relationships between the numbers of reported migraine attacks and rapid changes in barometric pressure. Cull (1981) found fewer occurrences of attacks when barometric pressure was low. This was partially attributed to a decrease in sunshine during low-pressure intrusions, as solar radiation is a suspected triggering mechanism for migraine onset. However, a Canadian Climate Center study (1981) found that migraines were most likely to occur on days with falling pressure, rising humidity, high winds, and rapid temperature fluctuations.

Rosen (1979) cites some startling relationships between pressure changes and human well-being. He describes research that indicates that cancer mortality rates seem to increase during low-pressure fluctuations, and deaths from circulatory diseases seem to increase during high-pressure fluctuations. He notes that rapid pressure fluctuations may penetrate buildings and propagate wave energy from their source like ripples in a pond. Humans appear to be quite sensitive to such changes.

The reduction of solar radiation by cloud cover may also have effects on well-being. By increasing the brightness level, the autonomic nervous system is affected by constriction changes in the eye pupil. According to Persinger (1980), this increases the rate of physical activity and leads to a general feeling of well-being. Wolfe (1981) notes that the sun's rays cause chemical changes in neurotransmitter or hormone synthesis in the brain, perhaps stimulating production of the hormone epinephrine, which stimulates the mind and body. Conversely, very low light intensities are often associated with states of relaxation, tiredness, and sleepiness.

F. POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON FUTURE HUMAN MORTALITY

Kalkstein (1986) estimated the potential effects of global warming on New York City. The study indicated that summer weather appears to have a significant impact on New York's present mortality rates, and a "threshold temperature" of 92°F was uncovered, suggesting that mortality increases quite rapidly when the maximum temperature exceeds this value. Days with 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 utilizing 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 developing weather/mortality algorithms for them.

Results shown in Table V-2 indicate 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 might be no different than today. It is likely, however, that economic conditions, as well as the basic structure of the city, will prevent full acclimatization; therefore, actual mortality may fall somewhere in between the estimated values. A similar procedure developed for winter indicated that mortality is minimally affected by severe winter weather in New York.

A preliminary precipitation/mortality analysis was also 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 following rain (but not snow) had significantly higher mortality rates than non-precipitation days.

G. SUMMARY

Although there is much literature concerned with the impact of weather on human mortality and well-being, it appears that the contributing researchers often disagree on the magnitude and specific nature of the impact, as well as on the role of acclimatization. General areas of agreement include:

1. Temperature extremes (both hot and cold) appear to increase mortality, although there is disagreement about which sex, age group, or race seems most affected.

2. Low relative humidities in winter appear to be directly related to frequencies of various illnesses and mortality.

3. Winter snowfall accumulations appear to correspond with periods of high mortality.

4. Rapid changes in the weather often induce a series of negative physiological responses from the body.

TABLE V-2

Average Monthly Increase in Total Mortality for the Various Warming Scenarios in New York a/, b/

Month	Degrees Above Present 0		1		2		4		5		7	
No Acclimatization												
June	19	(45)	34	(81)	57	(136)	114	(273)	156	(373)	253	(605)
July	86	(206)	110	(263)	154	(368)	282	(674)	372	(890)	622	(1,488)
August	25	(60)	37	(88)	64	(153)	170	(407)	250	(598)	487	(1,165)
TOTAL	130	(311)	181	(432)	276	(657)	566	(1,354)	778	(1,861)	1,362	(3,258)
Full Acclimatization												
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 1980 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.

There is a great need to quantify much of the subjective and intuitive information that has been published on climate/mortality relationships. Considering the enormous amount of mortality and morbidity data presently available from the National Center for Health Statistics, the Centers for Disease Control, and other agencies, more precise weather/health relationships should be uncovered in the near future. Perhaps one of the greatest challenges and areas of future research is determining the necessary cost to society to overcome climate stress. Changes in interior environments may be needed to overcome potential direct climate change impacts on living and working environments. Indirect impacts (e.g., the loss of productivity resulting from new climate conditions and increased insurance costs) have not been estimated. It is these impacts indirectly associated with human health/climate stress that remain important areas of research.

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