DOE/EV/10019-01
Volume 1 of 2

United States Department of Energy

December 1980

Assistant Secretary for Environment
Office of Health and Environmental Research

013

Carbon Dioxide Effects Research and Assessment Program

Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change: A Research Agenda

Volume I

CO2

DISCLAIMER

Printed in the United States of America

Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes

Printed Copy: $12.50
Microfiche Copy: $ 3.50

United States Department of Energy

Assistant Secretary for Environment
Office of Health and Environmental Research
Washington, D.C. 20545

December 1980
DOE/EV/10019-01
Uc-11

013

Carbon Dioxide Effects Research and Assessment Program

Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change: A Research Agenda

Volume I

A project conducted by the
American Association for the Advancement of Science
for the U.S. Department of Energy

Under Contract No. 79EV 10019.000

Project Steering Group

Roger Revelle, University of California, San Diego, Chairman
Elise Boulding, Dartmouth College
Charles F. Cooper, San Diego State University
Lester Lave, Brookings Institution
Stephen H. Schneider, National Center for Atmospheric Research
Sylvan Wittwer, Michigan State University

TABLE OF CONTENTS

Volume I

Preface

Introduction Intro-1

I. CRYOSPHERE, OCEANS, AND MARINE BIOTA I-1
West Antarctic Ice Sheet I-1
Northern Hemisphere Sea Ice and the Arctic Ocean I-4
Tundra, Taiga, and Permafrost I-7
Upper Ocean Circulation Patterns I-10
Marine Biota I-13

II. TERRESTRIAL BIOLOGICAL RESOURCES II-1

A. Direct Biological Effects of Increased Atmospheric CO_2 on Plants II-2
Biological Monitoring II-7

B. Climatic Effects on Cultivated Agriculture
Growing Seasons II-7
Alleviation of Environmental Stress on Renewable Resource Productivity II-8
Plant Protection II-12
Agriculture in Developing Countries II-14
Animal Agriculture II-16

C. Climatic Impact on Noncultivated Renewable Resources II-19
Impact of Climate Change on Forests II-20
Water Resources and Freshwater Ecosystems II-24
Grazinglands and Wildlife II-28

III. SOCIAL AND INSTITUTIONAL RESPONSES III-1
Societal Response Units III-2
Approaches to the Task: Research Areas and Workshops III-3
Data Collection III-6
Impacts on Society of Past Climate Changes III-8
Current Climate-Stress Surrogate Situations III-9
Societal Response Mechanisms III-10
Governmental Response Mechanisms III-13
International System III-15
Risk Perception, Information, and Decision Making III-16
Effects on Human Health III-19

IV. ECONOMIC AND GEOPOLITICAL CONSEQUENCES IV-1
Scenario Analysis IV-1
Economic Aspects of Scenarios IV-4
Social Aspects of Scenarios IV-5
International Issues IV-6
Modelling Issues IV-7

Appendix A Titles of Commissioned Papers, Volume II

Appendix B Contributors to Commissioned Papers

Appendix C AAAS Committee on Climate

FOREWORD

I view the publication of this particular volume in the Department of Energy's "CO2" series with something more than the usual satisfaction. This is because it is the first publication to appear in the extensive carbon dioxide literature that deals explicitly and substantively with the needed research into the impacts of a change in the climate system and an increase in CO2 on the remainder of the global environment and the effects of such an environmental dislocation on the world's societal system.

Further, the publication of this document marks the beginning of the end of the major part of the Department of Energy's planning activity; an undertaking that has involved 400 or more scientists since it began in late 1976. We will use this "Research Agenda" for developing our Comprehensive Plan, Part II and, as with Part I, offer Part II to all research organizations, in this country and abroad, as a basis for building a network of cooperative international research efforts.

It is with pleasure that I have this opportunity to recognize the efforts of Roger Revelle and his "managers," Elise Boulding, Charles Cooper, Lester Lave, Stephen Schneider and Sylvan Wittwer in bringing many of these new areas into focus for the first time. My association with these individuals has been as much a source of pleasure as of enlightenment. David Burns of the American Association for the Advancement of Science organized over a dozen workshop sessions, 30 commissioned papers and the efforts of the few hundred contributors listed in Appendix A and guided the convergence of all this activity into one document.

David H. Slade, Director
Carbon Dioxide and Climate Division
Office of Health and Environmental Research
Office of Environment
U.S. Department of Energy

Environmental and Societal Consequences of a CO2-Induced Climate Change: A Research Agenda is a product of a two-year collaboration between the Carbon Dioxide Effects Research and Assessment Program of the U.S. Department of Energy (DoE) and the American Association for the Advancement of Science (AAAS).

In 1978 DoE asked AAAS to organize a workshop dealing with the environmental and societal consequences of a CO2-induced climate change. Roger Revelle, a former president of AAAS, chaired the meeting, and five panels prepared reports on the physical, biological, agricultural, social, and economic impacts of climate change. The meeting was held in Annapolis, Maryland, April 2-6, 1979, and brought together 85 scholars, including a number from overseas. In addition to the panel reports, there were 28 contributed papers. (The Report of the Annapolis workshop, DoE publication CONF-7904143, is available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.)

The Annapolis workshop was the difficult first step in identifying the questions to be addressed by climate impacts research -- an effort which, as the Report stresses, requires strong multidisciplinary linkage across traditional intellectual boundaries. Nowhere else was this type of research being discussed and planned.

As a follow-up to the Annapolis meeting, DoE asked AAAS to undertake "Phase II" of the effects program. A Steering Group (composed of "managers" of the five topic areas discussed at the Annapolis workshop and chaired by Roger Revelle) directed this phase of the project.

The Steering Group met three times to plan the general approach to the project. There was also continuous correspondence as well as discussion by telephone. By late January 1980, the Steering Group had selected the specific topics that needed research. Experts were identified, and 30 papers were commissioned. Many of the principal authors of the papers chose to work with coauthors, or with the support of a research assistant or a small committee. Some papers were produced as the result of workshops. (Lists of the commissioned papers, principal authors and coauthors and their institutional affiliation, and participants in workshops, are given in the appendices).

Preliminary drafts were received in the spring of 1980, and there was considerable discussion and correspondence beween the authors and the Steering Group managers. These preliminary drafts were then revised. Each first draft was then sent to three expert reviewers, and their comments, criticism, and suggestions for improvement were sent to the principal author of the paper, and to the Steering Group manager with responsibility for that area. Authors discussed these reviews with the manager -- and revised their papers yet again.

The Steering Group met at the National Center for Atmospheric Research in Boulder, Colorado, July 14-17, 1980. They drew heavily on the commissioned papers, but felt that there were too many research projects recommended. They established priorities so that research which is truly essential can be distinguished from that which is merely interesting. Four days of discussion and writing produced a detailed outline and most of the text of this present volume. In some cases, material was quoted or paraphrased from the commissioned papers. The first draft was prepared by Barbara Riley, edited by David Sleeper and by David Burns, Director of the AAAS Climate Project, and was extensively revised by the Steering Group through several more drafts.

The draft report was reviewed by the AAAS Committee on Climate, and there were additional revisions as a result of this review. The final report plus the 30 commissioned papers, which provide much fuller discussion of the research issues, were delivered to the Department of Energy in November 1980.

The audience for this report is two-fold: On the one hand, it is addressed to scholars and researchers interested in the CO_2-effects area. The recommendations suggest major lines of research that their scientific colleagues believe are likely to be most productive. This report is also addressed to those institutions which might provide funding for CO_2-related research -- the Department of Energy, other U.S. departments and agencies, the Congress, foreign governments, international groups, and private foundations. It is intended therefore as a guide for preparing requests for proposals, and for evaluating proposals received.

This has been a lively, intensive, and significant project. Equally, it has been an instructive one for the AAAS in that it constituted a stiff test of its ability to assemble and focus interdisciplinary skills on a multi-dimensional task. The Board of Directors is grateful to all who shouldered the effort and saw it through.

William D. Carey
Executive Officer
American Association for the
Advancement of Science

In adding carbon dioxide to the atmosphere, mankind is unintentionally conducting a great biological and geophysical experiment. This experiment can be expected to increase scientific understanding of ecological systems and of the processes in the ocean and the atmosphere that partially determine world climate. But from the standpoint of governments and peoples, the major problem to be solved is to understand the nature of the impacts on societies of rising levels of atmospheric carbon dioxide (CO2)*, with the objective of avoiding or ameliorating unfavorable impacts and gaining most benefit from favorable impacts. The research program proposed herein is designed to provide the understanding needed to achieve this objective. It is based on a recognition of the distinctive characteristics of the CO2 problem.**

The Problem is Global. All countries of the world have contributed and will contribute CO2 to the atmosphere, primarily through combustion of fossil fuels and clearing of forests. The impacts of added atmospheric CO2 and of the climate changes that will almost certainly result will be felt, though in different ways, by all countries.

The Probable Outcome is Beyond Human Experience. The concentration of CO2 in the atmosphere is likely to be higher, and average temperatures in the lower atmosphere are likely to be warmer, than at any time during the last 100,000 years.

The Problem is Long-Range. If large quantities of fossil fuels continue to be used, there will be a slow, continuous increase in atmospheric CO2 and probably a slow, continuous rise in average atmospheric temperatures over the next one and a half centuries. Less likely, though not impossible, is a rapid change in climate at some future time to a new equilibrium state markedly different from the present regime. In either case, if large changes occur, they may be irreversible on a human time-scale, requiring several hundred to a thousand years before the added carbon dioxide is sequestered in deep ocean water.

*Properly, CO_2, but for convenience written in Volume I as "CO2".

**In the context of this report, the word "problem" means a challenge to human beings to find answers to important questions. It does not imply that undesirable consequences will necessarily result if the "problem" is not solved.

Societies have much experience in responding to short-term environmental catastrophes -- events such as hurricanes, floods, droughts, volcanic eruptions, earthquakes, or forest fires. But the expected changes from added CO2 will not be events, but rather slow, pervasive environmental changes, much like the inexorable movement of a glacier. They will be imperceptible to most people from year to year because of the normal interannual range of climatic variations. People and governments have little experience in consciously responding to such long-term, slow changes. However, responses may be more forthcoming if climatic extremes, such as exceptionally hot, dry summers, are superimposed on the underlying changes.

<u>The Global CO2 Problem is One Aspect of the Global Energy Problem</u>. The energy problem has become acute only during the last few years, but it is likely to become more and more serious during the next five or six decades. The consequences of rising levels of atmospheric CO2 could limit the available choices for solutions of the global energy problem. Most energy solutions will require very large expenditures for research, development, and production -- for example, the federal and private expenditures now being planned for converting oil shale and coal to fluid fuels. The possible future magnitude of the carbon dioxide emissions resulting from such conversion strongly suggests that a portion of these funds should be allocated to research on the carbon dioxide problem.

<u>The Role of the Less-Developed Countries Will be More Important in the Future</u>. The amount of energy used in the presently less-developed countries is likely to increase much more rapidly during the next 50 years than energy used in the developed ones. If the sources of energy in the devloping countries will be principally fossil fuels, these countries are likely to contribute a large share of the additional CO2 to the atmosphere.

In 1975, 29 percent of world commercial energy was used in the United States. By 2030, according to recent projections by the International Institute for Applied Systems Analysis (IIASA), the United States share will be only 15-17 percent, and the share of other industrialized countries, including the Soviet Union, Western and Eastern Europe, Japan, Australia, and New Zealand, will drop from 57 percent in 1975 to 43-45 percent. In 1975, the less-developed countries of Asia, Africa, and Latin America used 15 percent of world commercial energy. IIASA estimates that by 2030, these countries together will use 38-42 percent.

<u>International Agreements on Actions to Reduce CO2 Influx to the Atmosphere Will be Very Difficult</u>. In its use of energy and in the production of CO2 from combustion of fossil fuels and clearing of forests, we can expect that each nation and society will act in its own interests, if it has sufficient information about what these

interests are. International agreements on actions to reduce the influx of CO2 to the atmosphere are likely only to the extent that each nation sees such actions as being in its own interests.

The balance between costs and benefits from added carbon dioxide may be quite different for different countries. For example, the countries of the Indian subcontinent might benefit greatly if there were an increase in the regularity and intensity of the monsoon, while they might incur only small costs from the rather slight increase in average surface air temperatures expected at low latitudes. However, there is a marked asymmetry between consequences and causes. Though all countries will experience some aspects of the former, only three countries can play a decisive role in causing a large future increase in atmospheric CO2. Coal makes up 85 to 90 percent of the carbon in currently estimated fossil fuel resources, and nearly 90 percent of the world's coal is located in the Soviet Union, China, and the United States. The decisions of these countries concerning national uses and exports of coal will have a preponderant influence on the future rates and amounts of CO2 released to the atmosphere. Because of its relatively advanced mining and transportation systems, the primary responsibiliy for increased coal use in the next few decades will probably rest with the United States.

<u>Quantitative Estimates of Costs and Benefits are Not Now Possible.</u> At the present time, and perhaps for a long time to come, it will not be possible to make quantitative estimates of the costs and benefits to different countries of increases in atmospheric CO2.

Five kinds of uncertainty are involved:

First are the rates at which CO2 will be produced by world-wide combustion of fossil fuels, forest clearing, and other human activities, and the total quantities of CO2 produced up to given times in the future.

The second uncertainty is the magnitude of the "airborne fraction" -- that is, the partition of the CO2 produced by human activity among the oceans, the atmosphere, and the biosphere. This depends, among other things, on rates and amounts of afforestation, losses or gains of soil humus in deforested and cultivated lands, the nature of the ocean circulation (particularly the vertical components of advection, convection, and turbulent mixing), the quantity of organic carbon settling out of the photosynthetic zone in the sea into deeper water, and the rates of accumulation or oxidation of peat and other organic-rich sediments in marshes, wetlands, and estuaries. All of these factors can be expected to vary with changing CO2 concentrations in the atmosphere.

Third, the effects of added atmospheric CO_2 on temperature and precipitation in different geographical regions are uncertain. Present models allow estimates of changes in mean temperatures and precipitation at different latitudes, within a rather wide margin of error, but they give little insight into possible regional differences in these changes.

The fourth uncertainty involves the combined effects of added atmospheric CO_2, warmer temperatures, and changes in precipitation patterns on agricultural crop plants, domestic animals, agricultural pests, forests, other "natural" biomes on land, populations of fish and other marine organisms, and the cryosphere, including permafrost, sea ice, and the West Antarctic ice sheet.

And, finally, we are unable to estimate the impacts of all these effects on human beings and their societies, with their widely different capacities to respond and to adapt to change.

<u>But the Range of Probable Outcomes Can Be Estimated</u>. As our understanding of the carbon dioxide problem improves, we should be able to make better qualitative estimates of the range of probable outcomes. Such estimates could be used to lay a rational groundwork for policies and actions which would change the rates at which costs and benefits are incurred and increase the likelihood that benefits will exceed costs.

The range of probable rates at which carbon dioxide will be added to the atmosphere by human actions, and the factors that will slow down these rates, are clearly fundamental. Because of the close relationship between energy use and CO_2 emission, analytical studies should be undertaken to design a range of integrated world energy projections for the next 50 years, based on regional and individual country projections. Two world projections, one high and one low, have alrady been made by IIASA, but these differ by only about 40 percent, from 1070 quads of primary energy use in 2030 for the "high" projection to 670 quads*** for the "low" projection. Much lower projections could realistically be made, as may be seen by comparing the two IIASA projections for the United States (98 to 123 quads) with those made by the Committee on Nuclear and Alternative Energy Sources (CONAES) of the National Academy of Sciences (58 to 134 quads). All energy projections should take into account:

***One quad = 10^{15} BTU $\approx$ .25 x 10^{15} Kcal $\approx$ 3.6 x 10^7 tons of coal equivalent

- future growth of human populations in different countries and regions

- future regional and national energy needs per caput at different rates of economic growth

- kinds of energy (electricity, process heat, process steam, chemical products) needed for industrialization and increased food production, particularly in less-developed countries

- regional and national energy resources of all kinds, including hydro and wind power, geothermal sources, and potential uses of biomass and other forms of solar energy, as well as fossil fuel resources

- foreign exchange constraints in different countries on fossil fuel imports

- possibilities of energy conservation in transportation, industry, agriculture, and households -- for example, by use of more efficient cooking stoves, fuel-conserving vehicles, biological nitrogen fixation, and construction materials with low energy costs

- technological capabilities of different countries to construct and operate nuclear power plants

- future chages in the ratio of GNP to energy in different countries

- possibilities and costs of substituting small-scale dispersed generation of electricity, using locally available sources, for large-scale centralized generation

These energy projections should be examined in terms of the factors that could slow down the world-wide rate of CO_2 emissions. For example, even with modest rates of economic growth, the countries of East and South Asia, comprising half the world's population, will probably use more than 150 quads of primary energy in 2030, compared with about 35 quads today. But their rates of emission of CO_2 could vary by at least 50 percent, depending on the mix of energy sources. Besides slower rates of economic growth, which are undesirable for most countries, other factors that could reduce the influx of carbon dioxide to the atmosphere over the next 50 years are:

- a rapid expansion of nuclear power in countries with less coal reserves than the United Stats and the Soviet Union

- possible break-throughs in solar electric technology or in the use of solar energy to produce fluid fuels for transportation

- discovery and exploitation of large natural gas resources, particularly in developing countries where modern geological and geophysical exploration methods for hydrocarbons have just begun to be used (natural gas produces less carbon dioxide per BTU than other fossil fuels)

- the development of biomass fuel, especially in tropical less-developed countries

- the incentives for energy conservation that result from the high capital costs of energy development

- the production, transportation, and marketing constraints on the development of a world coal trade, bearing in mind that three countries -- the United States, the Soviet Union, and China -- possess nearly 90 percent of the world's coal resources

- the possibility that the present rapid destruction of forests in many less-developed countries could be stopped or even reversed within the next one to two decades

Some of these factors have been examined for conditions in the United States in the CONAES report, but they need to be considered in terms of the conditions in other developed countries and particularly in the developing countries, where the very uneven world distribution of fossil fuel resources and technical manpower and the high capital costs of energy development are serious constraints.

The levels of impact of several factors on world-wide rates of CO2 emission, notably expansion of nuclear power, major improvements in solar energy technology, development of biomass fuels, forest regeneration, and discoveries of natural gas resources will depend largely on research, development and application of new or advanced technologies. For example, a most desirable new technology would be production of adequate quantities of a fluid fuel for transportation that would not build up atmospheric CO2, yet would be less expensive in the future than such CO2-producing fuels as synthetic liquids from coal.

Most of the technologies that could slow down the rates of CO_2 emission are outside the scope of this report, which concentrates on research to elucidate the environmental and socioeconomic consequences of increased atmospheric CO_2. But an appraisal of the probabilities of success is essential for assessment of the CO_2 problem.****

Enhancing Benefits and Reducing Costs

Equally essential, and directly relevant to our environmental and socioeconomic concerns, is examination of the ways in which the benefits of higher atmospheric CO_2 can be enhanced and the costs reduced, with the possible objective of attaining a favorable ratio of benefits to costs. The possibilities appear most promising in agriculture and forestry. Under greenhouse conditions, where water and plant nutrients are abundant, high atmospheric carbon dioxide is known to act as a fertilizer which speeds up the growth of many crop plants and reduces their water requirements. Research is needed to determine the potential magnitude of these effects for field and tree crops and to enhance the effects through development of CO_2-responsive varieties. Biological and agronomic research should also be undertaken to reduce the stresses on agricultural crops and livestock, resulting from higher temperatures and lower water availability, that are likely to occur in many cultivated areas as the CO_2 content of the atmosphere increases.

Possible Effects not Susceptible to Human Action

Finally, we are also concerned with those effects of increased atmospheric CO_2 and climate warming which, if they occurred, would be difficult or impossible to modify by deliberate human action. We need to estimate the probability of occurrence of such effects, the approximate magnitude and timing of the deleterious (or beneficial) consequences, and the costs of societal adaptations to these consequences relative to the costs of stopping or drastically reducing the use of fossil fuels. Examples of such effects are the possible disappearance of the West Antarctic ice cap and of the Arctic Ocean sea ice, melting of permafrost in high northern latitudes, and the consequences for marine phytoplankton communities and coral reefs of a higher hydrogen ion concentration (lower pH) in near surface ocean waters.

Several questions of this kind relate to human health and behavior, and to environmental conservation:

****We assume that the goals of assessment are to articulate the main issues and central questions, to evaluate the implications of alternative choices and responses, to focus attention on critical uncertainties, and to identify key constraints -- scientific, technical, and political -- to more effective social action.

- What will be the effect of higher ambient CO_2 concentrations on human respiration and how will this -- if it exists -- affect human life expectancy?

- Given warmer average temperatures in mid-latitudes, will occasional very hot summers, resulting from interannual climatic variations, cause life-threatening stresses on physiologically vulnerable groups in human populations and among domestic animals?

- How will the projected fall in upper atmospheric temperatures interact with additions of chlorofluoromethanes and other gases to alter the ozone content of the stratosphere? How will the resulting change in solar ultraviolet radiation reaching the earth's surface affect human beings and other organisms -- terrestrial, fresh water, and marine?

- Will the present southward drift of human populations in the United States and other countries such as Finland and Canada be modified by the much warmer temperatures expected at higher latitudes in these countries?

- If climatic conditions for agriculture deteriorate in Mexico and Central American countries, will population pressures for migration to the United States be intensified? Or if agro-climatic conditions should improve, will economic development accelerate enough to slow migration?

- Will the rates of extinction of endangered species be accelerated by the expected climate changes, particularly species living near the upper limits of their temperature tolerance?

Social and Institutional Responses

We need to understand the ways in which societies and institutions are likely to respond to increased atmospheric carbon dioxide and climatic change, and to the accompanying environmental, economic and geopolitical consequences. What stresses on society will result? What determines the degree of vulnerability to stress on different societies and social groups? What stress-response capabilities presently exist or might be developed in the future?

Most social science research on response to change has dealt with short-term, high-stress, crisis situations. But in the CO_2 problem, our need is to understand societal responses to a slowly-changing climatic mean rather than to short-term extremes.

In attempting to evaluate the social impacts of a slow climatic change, society should be the subject of research -- not climate. Five societal response units must be considered: the individual, who processes signals and information concerning change, who holds attitudes and values concerning society, and who possesses certain skills in relating to society; the household, which is the primary adapting unit to change; the local community -- the neighborhood, village, town, or city; the nation, including both governmental and nongovernmental sectors; and the international system of relations among nations and cultures. Different types of societies should be studied, tribal and national, industrialized and nonindustrialized, together with the subcultures of different groups within societies.

Three Kinds of Research Are Needed

From the above discussion of the characteristics of the CO_2 problem, we may conclude that three kinds of research on the consequences of rising levels of atmospheric carbon dioxide and possible climatic changes are called for:

- Assessment of risks (and potential benefits) that could be averted only by limiting carbon dioxide emissions. This category includes possible changes of physical processes in the ocean and the cryosphere and effects on the biology of marine, fresh water, and terrestrial ecosystems in which effective human intervention is unlikely

- Research to enhance beneficial effects and lessen harmful ones, where this is possible, and to slow down rates of carbon dioxide emission

- Study of potential social and institutional responses to projected climatic changes

All three categories of research are encompassed in the recommended research projects given in the following chapters of this report. These projects have been selected by the Steering Group from a longer list of research topics suggested in the commissioned papers. Criteria for selection were, first, our estimate of the usefulness of the results in establishing a rational framework for national and international policies; second, the relevance of the proposed research to societal and scientific questions <u>outside</u> the CO_2 problem; third, whether the project addresses an answerable question, that is, the likelihood that significant results can be achieved within a reasonable time frame; and fourth, whether there is a need for a new or augmented effort beyond research already being conducted, usually for other purposes, which is applicable to aspects of the CO2 problem.

Many of the research areas in each category could be significant in laying a groundwork for public policy. Some of these, selected rather arbitrarily to illustrate the range and scope of the research required to study the consequences of rising levels of atmospheric CO2, may be summarized as follows:

Risk Assessment

1. Possible Disappearance of the West Antarctic Ice Sheet. This portion of the Antarctic ice cap is believed by some glaciologists to be unstable. If there were a marked warming in polar regions, it might disappear, causing a world-wide rise in sea level that would inundate many coastal cities and much valuable agricultural land. We need to be able to estimate the probability that this event could occur and the approximate rate, that is, whether the time involved might be measured in decades or centuries. As an analog of possible future deglaciation, an attempt should be made to determine if the West Antarctic ice cap disappeared during the last Interglacial period, about 120,000 years ago. Better understanding is needed of the dynamics of the ice streams flowing from West Antarctica, the relationships of these streams to ice shelves, and the effects on the ice shelves of the disappearance of seasonal pack ice and of heating of the surrounding ocean waters.

2. Effects on Artic Ocean Sea Ice. The Manabe-Weatherald model indicates that with a fourfold increase in atmospheric CO2, the cover of sea ice over the Arctic Ocean would disappear, at least in the summer time, with possibly profound changes in oceanic and atmospheric circulation. To be able to estimate the likelihood of this event and the possible consequences, greater understanding is needed of the dynamics of formation and dissolution of sea ice in the Arctic Ocean and the surrounding seas and of the interaction between the sea ice and the underlying waters.

3. Melting of Permafrost in High Northern Latitudes. With a sufficient increase in atmospheric CO2, climatic warming of 5°-10°C. might occur over land in high latitudes. This could result in extensive thawing of permafrost, with marked effects on the hydrology and ecology of the tundra. These areas of frozen ground contain large reservoirs of organic carbon in peat deposits, and probably also in methane hydrates a few hundred feet below the surface. Thawing of the permafrost, caused by climatic warming from an atmospheric CO2 increase, could result in oxidation of the peat and release of methane gas, and thus in a positive feedback effect on atmospheric carbon

dioxide. The magnitude of this effect would depend on the size, location, and present temperature-depth relationships of the peat and methane hydrate deposits. Reconnaissance surveys should be made to determine these quantities. Scientific cooperation with Canada and the Soviet Union is necessary because of the vast areas of frozen ground within these countries.

Research to Enhance Beneficial Effects and Lessen Harmful Ones

Far-reaching results can be hoped for from research of this kind applied to agriculture, forestry and animal husbandry, with the objectives of increasing productivity and attaining greater resiliency of agricultural systems under climatic change.

1. Biological Effects on Crop Plants of Increases in Atmospheric CO2. We have already pointed out that one of the principal benefits of increased atmospheric CO2 might be higher photosynthetic productivity and water-use efficiency in cultivated crops. Indeed, it is not impossible that a small part of the improvement in agricultural yields experienced during the past 50 years has resulted from the 13 percent increase in atmospheric CO2 content since the 19th Century. But much research is needed to take full advantage of expected future atmospheric CO2 levels. Studies should be undertaken to determine whether varieties of field crops can be developed, through conventional breeding programs and modern methods of genetic manipulation, that will have higher net photosynthetic production and use less water as the atmospheric CO2 content increases, but will not respond to a warmer atmospheric temperature by an increase in respiration that would cancel out the effect of CO2 fertilization. We are concerned both with more total plant production and an increase of the "harvest index," that is, the portion of the plant that can be used by human beings for food, fuel, fiber, or other useful products. The effects of higher temperature and increased carbon dioxide on biological nitrogen fixation and on weed, insect, and microbiological pests must be taken into account. Programs of genetic improvement should include greater resistance to pests as well as to other environmental stresses.

2. Improved Stress Resistance in Crop Plants. The climatic changes that are likely to accompany rising levels of atmospheric carbon dioxide will produce environmental stresses in many crop plants, resulting from higher average and extreme temperatures, and possibly also from lower water availability, the presence of atmospheric pollutants -- particularly oxidants -- unfavorable soil nutrient levels, increased soil alkalinity, or higher salinity. Research aimed at alleviating these environmental stresses should proceed along three parallel lines: studies of the basic biology of plant response and resistance to environmental stresses; genetic manipulation of crop varieties for greater resistance to environmental stresses; and

development of production-management systems that maximize the expression of genotypic stress resistance. The objective should be to improve average yields over relatively long periods, during which interannual climatic variations can be expected to occur.

In developing stress-resistant crop varieties, advantage must be taken of a wide variety of plant germ plasm. This will require a major expansion of present programs to preserve existing gene pools of important plant species, particularly in the developing countries of tropical and subtropical regions. Three kinds of work are needed: systematic collection, preservation, description, evaluation and cataloging of germ plasm of useful plant species; study of the requirements for long-term storage, viability, and preservation of variability; and research on gene recombinations to develop plant materials adaptable to environmental change and human needs.

3. Effects on Managed Forests. Biomass energy from forest trees can be at least partly substituted for fossil fuels, particularly in the tropics and subtropics, but this substitution will be possible on a sustainable basis only if the productivity of forests can be greatly increased. Research on the effects of increased atmospheric CO2 and higher temperatures on high-yielding trees of tropical and subtropcial regions under different conditions of water stress should be given priority, particularly on species that possess symbiotic nitrogen-fixing bacteria such as *Leucaena*, *Casuarina*, *Sesbania*, and various species of *Acacia*. In the future, the rapidly-growing energy demands of tropical and subtropical developing countries might be met in large part by renewable biomass fuels from forest plantations, with a consequent reduction in worldwide CO2 emissions.

4. Effects of Climate Change on Animal Husbandry. Meat, milk, eggs, and other animal products make up a large fraction of the world's agricultural output. The greatest concentrations of poultry and livestock production exist in the Temperate Zones, where a rise in average temperatures of more than 4°C. could occur if atmospheric CO2 is doubled. With presently-used animal varieties, nutrient intake and utilization and reproductive rates diminish with rising temperature, and the incidence of diseases may rise. Physiological research on metabolic and endocrine systems in domestic animals, under conditions of high average temperature and occasional extremely hot seasons, is needed to understand and quantify these effects. This should lead to improved management practices, including better dietary formulations, breeding periods synchronized with seasonal climate variations for most favorable conception and reproduction, low-cost animal shelters to buffer climatic changes, and selection of livestock and poultry varieties best suited to higher average and extreme temperatures. Attention should also be given to changes in the species composition of forage plants in grazing lands and cultivated pastures that could give higher nutrient concentrations.

In tropical and subtropical regions, the rise in average temperatures is expected to be relatively small, within the adaptive range of existing domestic animal varieties. But changes in precipitation regimes toward both more moisture in some regions and greater aridity in others will require adaptive research on animal feeding systems from rangelands, seeded pastures, cultivated forages, crop residues, and trees. Probable geographical shifts of disease and pest zones, following changes in the location of climatic zones, call for intensified research on prevention and control.

5. Better Management of Water Resources in Developing-Country Agriculture. The traditional agricultural systems of many developing countries will be especially vulnerable in regions where increased aridity results from carbon dioxide-induced climatic change. Capital investments in large irrigation systems will often be necessary, but improvements in management of irrigation water, based on site-specific applied research, could be even more important. Dependability of irrigation supplies is essential. In many river basins, this can be attained by conjunctive use of surface and ground waters. The greatest gains can be expected from improvements in on-farm water management. More than a doubling of the efficiency of use of irrigation water can be looked for, from less than 25 percent to more than 50 percent, by reducing losses in conveyance systems, controlling depth and uniformity of water applications, lessening evaporation losses, using simple methods for water measurement, and better timing of irrigations. Changes in cropping patterns, times of planting, and area planted will also often be desirable or necessary.

Research on Societal and Institutional Responses

1. Construction of Scenarios. Because of the important feedbacks among atmospheric and ocean dynamics, marine and land biota, and agriculture and energy use, the global CO2 problem can best be defined by constructing integrated simulation models -- that is, scenarios. A range of scenarios created by teams of physical, biological, and social scientists working together could constitute a framework for viewing the complex implications of the problem. These scenarios would have three major components: 1) a set of initial conditions, including the projections of world rates of energy use and carbon dioxide emissions discussed above; 2) cause-and-effect models that relate these initial conditions and perturbing forces (such as specific climatic changes) to outcomes; and 3) analyses of the implications of these outcomes. The objective should be to create plausible and internally-consistent combinations of assumptions and estimates about regional climates, ocean and ice dynamics, changes in marine and land biota, effects on agriculture, and societal responses. One part of these scenarios would be models of future international behavior and institutions that might result from the perceived self-interests of different nations. Uncertainties must be modelled

explicitly, with the aim of estimating the optimum flexibility and resiliency that societies will need in order to deal with uncertainties at the lowest practicable cost. The process of scenario construction should be iterative, with each round aimed at greater consistency and sharper definition of unanswered questions. By integrating available scientific information, scenarios can serve as powerful guides to further research.

2. Impacts on Society of Past Climate Changes. Global and regional climate changes will affect different societies and different segments within societies in a variety of ways. One means to determine the range of impacts is to undertake case studies on ways in which families, political institutions, and social sectors such as agriculture have been affected by changing or varying climates.

How have patterns of settlement, economic development, social relations, and people's attitudes and images about the future been modified? Historical case studies of climatically vulnerable areas such as Iceland and the Great Plains of the United States may be particularly useful in understanding societal adaptations. Studies of societal responses to "surrogates" for climatic change, e.g., long-continued soil erosion or relatively rapid changes in sea level, could also be helpful.

The basic resource for case studies should be a climate-society historical data bank, that is, a uniform, chronological set of data on climatic change over time and the impacts of these changes on societies. Initially, at least, the focus should be on the 13th Century to the present and on Europe and North America, but as opportunity offers, the data bank should be expanded to include other times and other cultures.

3. Risk Perception, Information and Decision-Making. Societies respond only to conditions they perceive. Consequently, a pivotal aspect of the carbon dioxide question involves how people in different cultures perceive scientific and other information and make decisions based on their perceptions regarding adaptation or other responses. In the industrialized countries, many kinds of experts will provide information on climate changes, and policy-makers at all levels of society will decide how to act on that information. The problem of perception raises several provocative and researchable questions in social psychology. How reliable are the judgments of experts and decision-makers? Where do personal biases creep into expert judgment? What kinds of information does the public need in order to comprehend the known and unknown? How will families perceive a problem and make decisions regarding their way of life? How do people combine multiple and conflicting risks and benefits of various options into a single decision? How can public opinion be accurately appraised as a guide to policy-making officials?

Climatic Data Bases and Monitoring

A research issue that cuts across all aspects of research on effects of CO_2-induced climate change involves making different kinds of data accessible and useful. Although the world inventory of weather and climate data is extensive, these have not often been reported in a form most useful for predicting biological and societal responses to climate change or climate variations. The desirability of improved historical and current climate data bases was pointed out independently by several groups involved in the preparation of this report. The form of these data bases should be determined by collaboration among biologists, agronomists, resource managers, social scientists, climatologists, statisticians, and data processing specialists. Different forms may be required for agriculture and for social sciences. In tropical agriculture, crop/climate data systems need to be built and tested that will include information on regional climate and agro-resources such as soil, topography, and socioeconomic conditions. Particularly for rain-fed agriculture, these data systems could be used in identifying, zoning and mapping areas suitable for different crops and cropping patterns, based on climatic and agronomic constraints. More generally, agroclimatic information combined with weather forecasts can be used at the farm level in selecting planting times and scheduling irrigation, fertilizer applications, and pest control measures. At the national level, it can be used for prediction of yields and prices.

Biological monitoring of forests and other natural ecosystems should be undertaken on a continuing basis to identify and evaluate effects of increased carbon dioxide and climatic change. Such monitoring should be carried out both on a reconnaissance level and in greater detail at specially-chosen sites, to study species successions and other relationships.

Many National and International Agencies Should Participate

Although the Department of Energy has assumed a leading role in planning research on the consequences of a high-CO_2 world, many federal and international agencies should be involved in developing and supporting the research program. For example, studies of the possible fate of the West Antarctic ice cap would appear to lie within the scope of the Antarctic Program of the National Science Foundation. The National Oceanographic and Atmospheric Administration and the Department of Defense have long been concerned with Arctic sea ice, while the behavior of Arctic permafrost has been extensively studied by agencies of the Defense Department and the U.S. Geological Survey. Basic biological research on plant responses to increased carbon dioxide could properly be supported by the National Science Foundation. The Department of Agriculture should be encouraged to support research and development on stress resistance and carbon dioxide response in crop plants and on the alleviation of temperature stresses in animal husbandry. The U.S. Forest Service and the Bureau of Land Management already conduct biological monitoring of changes in forests and grazinglands.

At the international level, research institutes of the Consultative Group on International Agricultural Research have begun to be concerned with problems of agricultural water management in the developing countries. UNESCO, through its program on Man and the Biosphere, is engaged in biological monitoring. Compilation and use of climate data for agricultural and other purposes is one of the primary goals of the World Climate Program sponsored by the World Meteorological Organization, in cooperation with the Food and Agricultural Organization of the United Nations. The United Nations Environmental Program has primary responsibility for worldwide climate-impact studies, including potential carbon dioxide impacts.

Workshops and Conferences

Scientists from a wide variety of disciplines in both industrialized and developing countries should be involved from the beginning in planning a research program on the direct biological effects on plants of rising atmospheric CO_2 levels. We recommend that the first step in planning should be the convening of a major week-long international conference. This conference could well have as many as 200 participants, and might be sponsored by the Department of Energy. The Proceedings of the conference should include recommendations for research projects, methodologies, and funding levels. In order to stimulate research throughout the world, the Proceedings should be published and widely distributed as soon as possible after the conclusion of the conference.

In the social sciences, there is scant precedent for much of the research needed to study the societal consequences of rising atmospheric CO_2 levels. Research organized by conventional disciplinary alignments would probably be less productive than interdisciplinary studies of major questions. In order to undertake the latter, methods for dealing with the issues should be developed and tested, and scientists of different disciplines and backgrounds must be helped to reach a common ground for cooperative work. We therefore recommend a series of seven relatively small research-design workshops which would bring together those who might become actively engaged in research on a particular question, together with consultants, prior to launching a research project. For example, one workshop might bring together specialists interested in historical case studies and the formation of a climate-society data bank; another might bring together scientists interested in on-site case studies of present-day stress situations which might be treated as climate surrogates.

The Commissioned Papers

As indicated in the Preface, more than 400 scientists representing many specialties participated in some way in preparing this report. The research recommendations encompass only a small number of the many suggestions in the 30 commissioned papers. These papers should be consulted for fuller discussion of questions concerning the consequences of a high-CO2 world and the possible resultant climatic changes, and for details of proposed research projects. In some cases, funding levels and manpower requirements are suggested, but these must be regarded only as order-of-magnitude approximations. Specific projects will, of course, require detailed proposals and budgets.

The Future of CO2 Impact Studies

This report is merely a starting point for what will doubtless be a long effort; the study of CO2-induced impacts on human affairs is just beginning. Because of the wide range of subject areas, the multi-disciplinary nature of the research, and the international implications of the problem, the further development of impact studies will almost certainly prompt useful new suggestions for research. These should be welcomed and incorporated into the global research program as it evolves.

Roger Revelle
Chairman
Project Steering Group

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

I

CRYOSPHERE, OCEANS, AND MARINE BIOTA

Research on CO_2 effects on the cryosphere and oceans should concentrate on the future of the West Antarctic ice sheet; the response of Northern Hemisphere sea ice and the Arctic Ocean to climatic warming; changes in permafrost in Asia and North America; changes in the circulation of the upper ocean; and effects on marine biota.

West Antarctic Ice Sheet

Most of the West Antarctic ice sheet is grounded below sea level. Because of this, it is thought to be relatively unstable compared to the remainder of the ice cover over Antarctica. The existence of a terrace about six meters above sea level in many coastal areas of the world suggests that this ice sheet disappeared during the last interglacial period about 120,000 years ago. We need to know whether this actually happened, and if so, at what rate.

If the West Antarctic ice sheet disintegrates because of warming of the ocean and atmosphere in high southern latitudes, sea levels would rise five to six meters. This would inundate many coastal cities and much presently productive farmland in the Netherlands, Bangladesh, the coastal lowlands of the southern United States, and populated river deltas throughout the world. The slower the rise in sea level, the easier social and economic adaptation would be, at least for the cities. Except for historical monuments, cities are constantly being rebuilt with a "half life" for most city buildings on the order of 50 years. An attempt to determine the rate of disappearance of the West Antarctic ice sheet during the last interglacial (and, of course, whether it disappeared at all) would therefore appear to be a research issue of the greatest importance.

Drilling through the ice sheet could throw light on this problem. One might expect to find a discontinuity in the annual ice layers corresponding to the last interglacial period, and the nature of this discontinuity might give an indication of the sequence of events. Ice cores should also give useful information about past climates, and the CO_2 content of the atmosphere during the last glacial period and the early part of the present interglacial. Careful paleontological and geochemical studies of remnant limestone reefs on high islands and in coastal areas of tropical seas could indicate approximately how rapidly the sea rose about 120,000 years ago years ago to a level several meters above its present sea level.

The dynamics of ice flow present another important research area, particularly in the Pine Island area of West Antarctica where the protecting ice shelf is absent or minimal in extent. Measurements, preferably at different depths in the ice sheet, should be made of the present rate of flow of the ice, and the relationship of this rate to the physical properties of the ice. Models of ice flow dynamics need to be further developed and checked by field observation. Satellite observation of the lateral extent of sea ice and of the ice shelves around Antarctica as well as the surface topography of the ice sheet should be planned with the objective of establishing a monitoring program to be continued over the next several decades. (For a further discussion of the questions raised and the research proposed, see paper by Charles Bentley, Volume II.)

PRIORITY RESEARCH:

o Deep Drilling in the Ice Sheet. Bore holes should be drilled and cored from top to bottom of the ice sheet in both East and West Antarctica. The East Antarctic cores may provide a record of ice accumulation for the last 150,000 years or more, while the West Antarctic cores might show a hiatus about 120,000 years ago (when the West Antarctic ice sheet presumably disintegrated) and a subsequent sequence of ice formation when the ice reappeared during the last glacial period. Precise dating of the ice layers deposited during the past 20,000 years or so is possible using ^{14}C, and for greater ages using the relative abundance of ^{36}Cl which has a half-life of 300,000 years. Measurements of the ratios of stable oxygen isotopes, $^{18}O/^{16}O$, can be used to elucidate fluctuations in air temperatures, as can stratigraphic indicators of melt phenomena which occurred at the time of ice formation. Recent work has shown that ice cores also contain minute quantities of air (including CO2) from the time when the ice sheet was formed. Results from both Greenland and Antarctica indicate that atmospheric CO2 was probably not more than 200 parts per million (ppm) toward the end of the last glacial period, rising to perhaps 350-400 ppm during the early stages of the present interglacial.

To drill and core these deep holes in the ice, equipment capable of penetrating cold ice to depths greater than 1,000 meters must be used. (Below this depth drilling fluid becomes essential to prevent hole collapse). Denmark, France, and the Soviet Union are experimenting with deep drills; the United States is participating in the Danish deep drilling program in Greenland and is assessing the possible application of the Danish drill in Antarctica.

Development and testing of the equipment for Antarctic use and the drilling itself should probably be under the sponsorship of the Antarctic Program of the National Science Foundation. Geochemical laboratories in several countries could undertake the studies for dating the ice, determining past carbon dioxide concentrations, and making estimates of climatic variability from stable oxygen isotope ratios.

o Worldwide Study of Terraces above Present Sea Level. Well-preserved fossil corals in late Pleistocene wave-cut and depositional terraces at 21 localities throughout the world have been dated by measurements of the ratios of uranium and thorium isotopes.* At almost all localities, a high sea level about 7 meters above the present occurred 120,000 years ago. A somewhat lower high stand of the sea -- perhaps 2 meters above present sea level -- appears to have occurred 135,000 years ago. As shown by oxygen isotope ratios in deep sea sediments, this earlier high level was accompanied by a major melt-water event in the Gulf of Mexico, which may have been caused by melting of the Northern Hemisphere ice cap. The higher stand 120,000 years ago could have resulted from the temporary disappearance of the West Antarctic ice cap. If this happened quickly, a surface layer of low-salinity water might have persisted long enough to leave a measurable trace in the $^{18}O/^{16}O$ ratio of the oldest coral fossils on the terraces. A rapid rise might also be indicated if coral and algal species that grow best a few meters below the surface were found near the bottom of the depositional terraces, underneath remains of shallower water organisms. These studies call for cooperative research between geochemists and paleontologists.

o Drainage Basin Studies. Most of the West Antarctic ice sheet can be conveniently subdivided into a number of major drainage basins which can have different states of mass balance (difference between accumulation and melting rates of ice masses), and react differently to external changes. Two of these basins are of greatest present interest: the Amundsen Sea Drainage Basin and the Ross Sea Drainage Basin.

*W. S. Moore, "Late Pleistocene Sea Level History" in Uranium - Series in Disequilibrium: Applications to Problems in Earth Science. Edited by Miro Ivanovich and Russ Harmon. Oxford University Press. 1981 (in press).

Amundsen Sea Drainage Basin: a) The present-day grounding lines of Thwaites and Pine Island Glaciers should be located accurately. b) The ice discharge velocity and flux across these grounding lines should be measured (in part by remote sensing.) c) Surface and bed topography must be mapped so that the ice drainage systems of Thwaites and Pine Island Glaciers can be accurately determined, and boundary conditions for numerical modelling experiments established, including subglacial meltwater where it exists. d) Snow accumulation rates and surface temperatures for the Thwaites and Pine Island Glacier drainage systems should be measured at a grid of surface data stations. e) A corehole to bedrock should be drilled through the low ice-divide saddle between the Amundsen and Weddell Sea drainage basins to determine whether this saddle has recently lowered and/or migrated. f) Precision elevation profiles, possibly using laser or radar satellite altimetry, should be completed of Thwaites and Pine Island Glaciers' flowlines. g) The expansion of ablation (melting) zones of Thwaites and Pine Island Glaciers should be monitored (possibly by satellite imagery using reflectivity and microwave emissivity) as indicators of response to climatic warming.

Ross Sea Drainage Basin: The program in the Ross basin should be similar to that in the Amundsen basin except that the bedrock topography has already largely been mapped. The emphasis should be on Ice Streams B and C, because Ice Stream B is one of the most active, whereas Ice Stream C may recently have diminished substantially in its activity. Existing data suggest that the contrasting behavior of these ice streams is inconsistent with steady state. We need contemporary surface mass balance measurements along with flow lines from the ice divide to the ice shelf, with supporting velocity and strain rate data. Ice temperatures should be determined in all drill holes as an indicator of any recent climate change. At some locations the ice shelf should be penetrated by temperature sensors, some frozen into the ice itself and others in the water column below the ice.

Northern Hemisphere Sea Ice and the Arctic Ocean

According to the Manabe-Stouffer model (a global circulation model developed at NOAA's Geophysical Fluid Dynamics Laboratory at Princeton, showing a theoretical climatic response to changes in atmospheric carbon dioxide) a sufficient increase of the atmospheric

CO_2 content could result in a disappearance, at least during the summer months, of Arctic Sea ice. This would have profound effects on the transfer of heat and water vapor between the sea and the air in high northern latitudes, and also perhaps on the formation of Atlantic deep and bottom water. Diminution in the extent of sea ice cover would markedly decrease the earth's albedo (or reflectivity) and thus probably modify oceanic and atmospheric circulation patterns.

The current seasonal and interannual fluctuations of the extent of the sea ice need to be understood. These fluctuations are monitored using satellites and other means, by Soviet, Canadian, American and other governmental agencies. But the thermal, chemical, and mechanical processes involved should be clarified by experimental research and theoretical modelling, particularly the processes of heat transfer between the ice, the underlying sea water, and the overlying air. (The present NOAA, NASA, Navy, and Air Force program of satellite images for preparation of ice charts, and scientific analysis of sea ice data, can provide more precise information about variations in the extent of sea ice cover.)

A second set of research issues concerns the sinking of chilled high salinity water from leads -- large areas of open water -- between masses of sea ice. At the present time, relatively large quantities of fresh water are carried to the ocean by Siberian rivers. This fresh water spreads out in a thin layer over the more saline sea water, resulting in a considerable vertical stability of the water column and a corresponding inhibition of vertical turbulent exchanges of heat and salt. What would be the effect on the Arctic Ocean sea ice of a climate change that greatly changed the flow of these rivers? This question may be answered if the Soviets carry out their proposed scheme of diverting the flow of Siberian rivers from north to south. A cooperative study with the Soviets of this question should be undertaken. (See paper by Norbert Untersteiner, Volume II.)

Modelling. We need to consider how to accelerate progress in predictive skill of a number of highly promising models, integrated with the development of global ocean-atmosphere interactive models, as part of a comprehensive national plan. Progress in some areas is hampered by a shortage of data, but there appears to be no shortage of ideas. Access to computers to test and develop them is necessary.

A shortage of scientific manpower is the most serious constraint on Arctic research. Long-term funding and other incentives are required for the formation of strong scientific groups that will attract talented young scientists to Arctic research and offer them opportunities for professional advancement.

Priority research involving northern sea ice should concentrate on monitoring. Monitoring should aim to provide data on the wind stress field; heat exchange between ocean water and sea ice; and heat exchange between sea ice and the atmosphere. The data should have a sufficient spatial resolution to provide useful parameters for a dynamic sea ice model on short and long time scales.

PRIORITY RESEARCH:

o Data Buoy Program. Air-dropped data buoys on sea ice could report atmospheric surface pressure, temperature (during the sunless time), and position (to about 1 kilometer accuracy, via the TIROS satellite). Air-dropped buoys on open water or thin ice would provide the same data as the buoys on sea ice, and add measurements of water temperature and salinity via a cable with temperature and conductivity sensors. Measurements from a network of upward-looking sonic devices to measure ablation and accretion at the ice bottom, combined with observations of the temperature gradient in the water near the ice bottom, can be used to determine the upward flux of heat in the ocean.

o Fram Strait Water Exchange. Warm Atlantic Ocean water flowing through the Fram Strait plays a major role in the heat budget of the Arctic Ocean. The existing program of monitoring the West-Spitsbergen Current can provide information about the largest component of the water, heat, and salt exchange between the Arctic Basin and the World Ocean. The addition of narrow beam, upward-looking sonic transducers to monitor the volume of ice export from the Arctic Basin would provide important information.

o Arctic Ocean Circulation. Establish the regional and temporal variability of the oceanic circulation and the formation of "arctic intermediate water." Time series of variations in the upper layers can be made using thermistor and salinometer strings on data buoys. The circulation of deep water masses can be inferred from tracers such as tritium, radioactive carbon, Freon, or DDT (whose input can be dated). Water samples and salinity and temperature profiles to the ocean bottom would also be important. Transects by a nuclear submarine could collect water samples for trace constituent analysis in a large horizontal survey of the shallow water (60-80 meters) chemical oceanography. In addition to water samples, the submarine could also operate its narrow beam, upward-looking sonar profiler to yield ice-thickness data. This would be particularly useful if transects were performed both during maximum ice thickness in the spring, and in summer at the start of freeze up. The data would provide a test of dynamic ice models.

o Shelf-Land Interactions. Research should examine the oceanographic and climatological significance of land-sea interactions such as river input and mixing, and other processes which affect the density gradient. An expert panel could collect and evaluate the abundant Soviet literature on this subject; recommend how to use the data to advance research; develop a plan to assemble pertinent meteorological data and satellite images, and to acquire new data from buoys, ships, and aircraft; and define and prioritize a series of model and sensitivity studies.

o Role of Sea Ice in CO_2 Uptake by the Polar Oceans. The existence and magnitude of the effect of sea ice on the uptake and downward convection of CO_2 in polar oceans should be determined by measurement of CO_2 in the air and water in the seasonal sea ice zone.

o Field Work in the Seasonal Sea Ice Zone. A large international effort is needed to acquire data by ship, aircraft, and satellite. This should be combined with analysis of existing data and the development of more sophisticated models. The aim is to understand and predict the behavior, including feedbacks to the global climate system, of this zone of vigorous interaction between ocean, ice, and atmosphere.

Tundra, Taiga, and Permafrost

Recent discussions of global carbon balance have emphasized the world distribution of biomass and its significance in the global carbon balance. Attention has focused on the carbon budget of the tropical rain forest because of its large biomass and rapid rate of exploitation. Much less attention has been placed on ecosystems north of about 60 degrees which have low annual productivity and low standing crops of carbon above ground, but have large areal extents, massive accumulations of peat, and high sensitivities to climate change. Much of this area is underlain by permafrost, or perennially frozen ground, ranging in thickness from less than a meter to about 1,000 meters. General circulation models of the atmosphere indicate that a rise in CO_2 will cause the greatest temperature increase at latitudes above 60 to 70 degrees N, the zone of tundra, taiga (boreal conifer forest), and permafrost.

During the last 10,000 years, northern ecosystems have accumulated quantities of carbon in dead organic matter equal to about 10 percent of the organic carbon currently in world terrestrial ecosystems. Recent data also suggest that a quantity of carbon possibly equal to the amount in northern soils is incorporated in permafrost as methane hydrates (a hydrate is a compound formed by the union of water with some other substance).

The effect of climate change on carbon loss or accumulation rates in northern ecosystems and permafrost is poorly known. More precise estimates are critical because if the carbon balance of terrestrial systems becomes negative with increased global temperature, increased carbon dioxide released into the atmosphere may have a positive feedback, hastening the projected global rise in temperatures.

The effect of temperature on the carbon accumulation or loss rate is both direct, through the different temperature responses of photosynthesis and decomposition, and indirect, through the effects of temperature on soil thaw, exposure of buried peat layers, drainage and soil aeration, mineralization of limiting nutrients (usually nitrogen or phosphorus), and increased nutrient availability. Methane would be released upon melting of permafrost; the rate of melting would depend on interactions of temperature and the insulating effect of vegetation.

The impact of warmer temperature on the carbon accumulation or loss rate will be both direct, through the different temperature responses of photosynthesis and decomposition, and indirect, through the effects of higher temperature on thawing of frozen ground, exposure of buried peat layers, drainage and soil aeration, mineralization of limiting nutrients (usually nitrogen or phosphorous), and increased nutrient availability. Methane would be released upon melting of permafrost; the rate of melting would depend on interactions of a warmer atmosphere with the buried ice under the insulating effect of vegetation.

International cooperation in research on CO2 effects on tundra, taiga, and permafrost is essential and feasible. These circumpolar resources are held by a few developed nations: Canada, the U.S., the Soviet Union, Finland, the Scandinavian countries, and the United Kingdom. All have active polar research programs. There is good personal and scientific interchange among these programs, stemming from the high degree of international cooperation achieved by the Tundra Biome Project of the International Biological Program in the early 1970's. Strong efforts should be made to facilitate international cooperation in research on CO2 effects in the far north. (See papers by Jerry Brown and John T. Andrews, and Philip C. Miller, Volume II.)

PRIORITY RESEARCH:

o Monitoring Temperature Changes in and over the Permafrost. Deep-ground temperature measurements at drill holes which have been measured previously should be repeated periodically. New holes that become available through petroleum exploration, and at additional sites, should also be measured. Soil temperatures at a standard depth in the active layer should be monitored routinely at weekly to monthly intervals. In Canada, these observations are made at airfields and weather stations. In Alaska, virtually no systematic measurements of soil temperature are made. Closely associated with soil temperature measurements should be measurements of active layer thickness. Both kinds of observations need to be made on specific landscape elements which are likely to be modified by climate change -- for example, south- and north-facing slopes in the taiga, and areas with known fire histories.

o Climatic Interpretations. Climatic variables used in estimating regional water and energy budgets, are solar radiation, air temperature, wind velocity, cloud cover, humidity, and precipitation. The available records for a number of tundra and taiga stations on at least a monthly frequency need to be analyzed to determine how warm and cool interannual variations are correlated with other meteorological variables and conditions that exist simultaneously over a broad area. This perhaps could be carried out as part of the climatic data base project recommended in Section III.

Based upon increased understanding of climate-induced changes in the deep-ground temperatures and upon the correlation of climatological variables, simulation models of permafrost temperatures should be further refined and tested. These would provide simulations of ground temperature as surface atmospheric conditions change.

There should also be a search for past climate analogues -- times in the past when the climate approximated the conditions that might occur in the early stages of a high-CO_2 world. It is recommended that detailed pollen investigations be undertaken in northern Alaska to determine climate change during the Holocene (about 12,000 years before the present). More work is now in progress throughout Alaska, but only a few studies have been undertaken on the North Slope. It appears that all the ingredients are available for a detailed and comprehensive study of the Holocene vegetation/pollen/climate changes along the same lines that have been used successfully in arctic Canada. Such a study could establish analogues for some of the conditions that might result from increasing atmospheric CO_2.

o Field Interpretations. Peat thickness should be correlated with vegetation types in bogs and other peat formations, especially in southcentral and western Alaska where they are more extensive than in interior and northern Alaska. Extrapolations using remote sensing can then be applied for reconaissance surveys of the total volume of peat at different depths in the permafrost.

Detailed observations over a 10-20 year period should be conducted on representative thaw lakes to determine their growth and contraction patterns as a function of present climatic variations. Associated studies should be conducted of the lakes' water balance. Interpretation of present and historical thaw lake evidence should provide insight into permafrost modifications resulting from climate change. Since Arctic lakes are potential carbon sinks, their relative importance to the high latitude carbon cycle should be established.

o Northern Animals. Studies should be done regarding aspects of animal and socioeconomic ecology which will be potentially important politically with CO_2-induced climate change. Biologists, economists, sociologists, and others should investigate the effects of climate change on human interactions with animal populations, including large and small mammals, insects, migratory birds, and other animals which are important for social, political, and economic reasons.

o Extent of Future Oxidation of Organic Carbon in Soil and Peat Deposits, and Release of Methane in Permafrost. Studies should be undertaken to estimate the quantity of presently immobilized carbon in permafrost that might be released with rising temperatures. The CO_2-induced temperature increase is expected to be several times greater at the poles than the global average increase. The consequent thawing of areas of permafrost will expose large reservoirs of organic carbon to oxidation. This may result in a possibly significant positive feedback, increasing the amount of atmospheric CO_2. Similarly, the thawing could also release methane hydrates now sequestered in permafrost. Under appropriate temperatures and pressures, ice lattices can physically trap methane molecules without formation of chemical bonds. Melting could release at least some of this carbon to the atmosphere (some would remain in liquid water). The carbon in this source, though the least well understood of the large carbon reservoirs, could possibly exceed the amount currently stored in northern soils.*

Upper Ocean Circulation Patterns

Models used to estimate the climatic effects of increased atmospheric CO2 do not take into account the quasi-horizontal current motions of the ocean waters. The upper ocean has a mixed layer averaging about 70 meters deep which exchanges heat and water directly with the atmosphere. Both the box and diffusion models used to estimate the quantity of CO2 taken up by the ocean consider only vertical diffusion as a means of downward transport of CO2, when actually four oceanic processes are involved. Measurements of the oceanic distribution of tritium produced by atomic weapons tests in the 1950's indicate the processes are: 1) downward vertical diffusion within the mixed layer and across underlying density layers; 2) horizontal diffusion within layers of relatively constant density; and 3) convective overturning of cold surface and deep waters in high latitudes; and, 4) advective motions along equal-density surfaces. It would be expected that CO2-induced warming of the lower atmosphere would affect all four processes.

Another important question concerning the effect of climate change on the oceans involves heat transport. By observing radiation balances at the top of the atmosphere, the total amount of heat transported from low to high latitudes has been fairly well determined. But considerable uncertainty exists concerning the relative roles of the ocean and the atmosphere in this heat transport. Until the quantity of heat transported by the ocean is better understood, models of the climate changes resulting from increased atmospheric CO2 will be uncertain.

One promising analogue for ocean circulation studies is the so-called Altithermal or Hypsithermal, a period 5,000 to 8,000 years ago when average atmospheric temperatures were perhaps more than one

---

*Keith A. Krenvolden and Mark A. McMenamin, "Hydrates of Natural Gas: A Review of Their Geological Occurrence." U.S. Geological Survey. Circular 825, iii plus 17 pages, 1980.

degree C. warmer than at present. Recent evidence from analyses of ice cores from Greenland and Antarctica indicates that atmospheric CO_2 levels during the Altithermal may have been higher than current levels. Careful studies of pelagic (ocean surface) organisms in ocean sediments deposited during the Altithermal could provide important information about possible changes in upper-ocean circulation patterns. (See paper by Michael McCartney and Henry Lansford, Volume II.)

PRIORITY RESEARCH:

o Mechanisms and Dynamics of Upper Ocean Circulation Patterns. Detailed studies of the mechanisms and dynamics of the major upper ocean circulation patterns under present conditions should provide greater understanding of the nature and direction of future changes induced by rising levels of atmospheric CO_2. This research should focus in particular on the vertical mixing across the winter thermocline in high latitudes to determine how these processes vary from year to year under the influence of present interannual climatic variations. (A thermocline is a layer of water between the warmer, surface zone and the colder, deep-water zone.) Also, better measurements are needed of the rates of mixing and advection along surfaces of constant density (isopycnal surfaces) -- both those that outcrop at high latitudes and those formed by mixing across or within the thermocline. A variety of chemical tracers can be used in these studies, including tritium, ^{14}C, radioactive cesium, and nonconservative tracers such as oxygen and CO_2.

o Heat Transport. An experiment being planned by the ICSU/UNESCO Committee on Climate Change and the Ocean to measure the meridional heat transport in the North Atlantic between the latitudes of 20 and 40 degrees N ("Cage" experiment) should result in a much improved estimate of the poleward transport of heat by ocean waters and the mechanisms by which this occurs. It should be supported. Ultimately, it could lead to a marked improvement in general circulation models of climate and the potential alterations resulting from changing boundary conditions such as higher atmospheric CO_2 content. This research will require international cooperation and support.

o Altithermal Ocean Sediments. The $^{18}O/^{16}O$ ratios in the shells of pelagic organisms found in sediments deposited during the Altithermal should give detailed information on the geographical distribution of changes in subsurface ocean temperatures and circulation. Some cores already collected by the Deep Sea Drilling Project can be used for this purpose. However, the resolution of these cores is low in most cases because of "bioturbation" caused by bottom-dwelling organisms and also because the drilling process tends to disturb the sediment. Attempts should be made using other coring means, such as the "piston corer" recently developed in the Deep Sea Drilling Project, to obtain cores with better resolution, particularly in areas of anaerobic bottom conditions where annual layers are preserved. Studies of these annual layers could give very important clues concerning the interannual variability of climate under conditions of higher atmospheric CO_2. Studies of varves (pairs of silt or clay layers believed to correspond to annual cycles of deposition) in undisturbed lake sediments should be combined with studies of climate data from tree rings to give further knowledge concerning regional climates during the Altithermal.

o Work should be supported to determine whether increased precipitation (and presumably increased runoff) might affect the sequestering of river-borne carbon on continental shelves. (See paper by Charles Coutant, Volume II.)

Marine Biota

An increase in atmospheric CO_2 would have both direct and indirect effects on marine organisms -- direct effects through the increase in dissolved CO_2 in the subsurface ocean water and indirect effects through the warming of the atmosphere and the ocean.

A warming of the atmosphere and the surface ocean layers could result in an increase in the vertical stability of ocean waters in or just below the euphotic zone and this in turn might affect the distribution of nutrients for phytoplankton.

The increase in dissolved carbon dioxide in areas such as some estuaries and offshore waters where other nutrients are abundant could result in an increase in the net primary production of phytoplankton. A fourfold increase in atmospheric carbon dioxide would bring about a decrease in the pH of surface seawater from its current average level of 8.1 to about 7.5, and the concentration of carbonate ion would be significantly lowered. Photosynthesis in phytoplankton follows the C_3 biochemical pattern in which both photosynthesis and photorespiration occur during the hours of sunlight. In general, photorespiration as well as photosynthesis in C plants are relatively sensitive to the concentration of CO2 in their environment. Various groups of phytoplankton organisms may respond differently to CO2 increases depending on the levels of phosphate and other nutrients present. Thus a higher environmental CO2 concentration may alter the composition of the phytoplankton community, with a consequent alteration in the oceanic food web and therefore of the populations of fish and other organisms useful to humans. (A simple food web usually results in a higher production of harvestible organisms relative to primary photoplankton production.)

Another important issue regarding the effects of rising atmospheric CO2 levels on marine life involves the rate of sedimentation of both land-derived and marine organic carbon on continental shelves and the processes by which this material is removed from the shelves into the deeper ocean. Some scientists have contended that the annual removal of organic carbon from the water column on the continental shelves may correspond to as much as one billion tons of carbon per year, which would represent a significant part of the overall carbon flux. Carbon from rivers enters the marine environment in estuaries as elemental carbon from fires and dissolved and particulate organic matter. The basic question is how much of the organic carbon is oxidized in nearshore and offshore waters. New means to trace river carbon from land through estuaries to the open ocean and sediments are required. How refractory is this material on entering the sea? What is its probable turnover time and the likelihood of burial?

The higher concentration of dissolved carbon dioxide and the accompanying lower pH and carbonate ion concentration in tropical subsurface ocean waters could lower the rates of deposition of calcium carbonate in reef-building corals and coralline algae. This effect might be partially counteracted by somewhat higher water temperatures, and by increased photosynthetic production of the symbiotic zooanthellae of the coral organisms. Controlled experiments on the growth of reef-building organisms at different temperatures at CO2 partial pressure could help to resolve this question. (For further information, see paper by Osmund Holm-Hansen, Volume II.)

PRIORITY RESEARCH

o <u>Changes in the Stability of the Water Column.</u> An important question involves whether primary production would be affected by decreased upwelling and greater water-column stability. At higher latitudes, biological production is limited primarily by the amount of radiant energy, and at lower latitudes primarily by nutrient supply. The predicted CO_2-induced climate change may alter ocean dynamics such as upwelling. As a general prediction, one would expect production at higher latitudes to increase and at lower latitudes to decrease. Of particular interest in this connection are: a) one-dimensional or two-dimensional theoretical studies of the upper turbulent boundary layer, particularly of seasonal changes; b) theoretical studies of the effects of mixed layer processes on primary and secondary production, emphasizing nutrient transport by seasonal entrainment (the transport of nutrients in currents); c) analysis of existing and new data to obtain a global description of seasonal changes in mixed layer depths, euphotic depths, and depth of the nutracline (area of water with rapidly increasing levels of nutrients), so as to predict the sensitivity of planktonic ecosystems to changes in heat transport at the turbulent boundary layer; d) studies of sea surface temperature and color, via remote sensing, which can detect climatically induced regional shifts in production; e) experiments to examine the rates of ammonification and nitrification in the sea, and the response of bacterioplankton to climate change; and f) examinations of paleontological records such as phosphatite deposits as an analogue of the biological effects of changes in upwelling.

An additional area of inquiry involves the effect of increased water-column stability on the relation between primary production and the rate of input of organic carbon to the benthos. Two methods of addressing this question are: a) use ^{15}Ni-labelled substrates to measure the flux of nitrogen through ammonia, nitrate, nitrite, etc., as related to primary production; and b) use of particle interceptor traps at various depths to measure the amount of organic matter descending in the water column as a function of the nutrient status of the euphotic zone.

o Primary Production in Phytoplankton and Increased CO_2. Would increased CO_2 levels significantly affect the rate of primary production in the marine environment? The effects of higher CO_2 concentrations on rates of photosynthesis and photorespiration of different groups of phytoplankton should be studied, both in laboratory cultures and ocean "microcosms" (large transparent enclosures, suspended at different depths in the euphotic zone, which contain local plankton communities).

o <u>pH Levels and Phytoplankton, Zooplankton, and Fish Larvae</u>. How would lowered pH affect the chemical activity of inorganic and organic solutes which influence the marine biota? Laboratory and ocean-microcosm experiments should be undertaken to determine the effects on marine life of lower pH levels caused by rising atmospheric CO_2 concentrations. Studies should focus on phytoplankton, zooplankton, and fish larvae.

Chemical activities of dissolved substances in sea water should be studied to understand the chemical state and activity of the most important nutrients, and biologically active constituents trace including direct physical-chemical study of ionic species, complexation reactions, ligand binding constants, etc. at different pH levels.

Would a pH decrease of 0.5 units have significant effects on plant or animal cells? Laboratory and controlled field studies should investigate: a) biochemical/enzymatic states of isolated enzyme systems from representative marine plants and animals; b) membrane-bound transport systems, particularly those maintained by light-mediated electron transport in marine flora; c) sensitivity (under controlled conditions) to change in CO_2 and pH of representative marine zooplankton, invertebrates, and fish larvae; and d) the long-term effects of lowered pH on macrophytes and benthic communities, with special attention to changes in respiratory and photosynthetic rates and possible resultant shifts in community structure.

Many, though by no means all, of the effects on society of increasing atmospheric CO_2 will result from changes in terrestrial biological resources used by man. These include food, feed, fiber, and energy crops, food animals, range and forage crops, forests, fisheries, and wildlife. Important esthetic, recreational, and amenity resources will also be affected.

There are two categories of biological response to increased CO_2. The first is a direct effect. CO_2 is essential for photosynthesis and plant growth. Indeed, it is sometimes the limiting factor; CO_2 fertilization of crops grown in greenhouses is a common means of increasing production. The direct biological effect of an increase in atmospheric CO_2 is expected to be neutral or beneficial, at least with respect to plants. Harmful effects of CO_2 on biological processes of higher plants are apparent only when its concentration exceeds about 1,000 ppm -- three times the present level. Effects on animals are somewhat more problematical and may require additional investigation. Any adverse effects are expected to be small -- perhaps near the limits of detection.

The other effect is climate change. The general projected trend will be a warming, but some places could get cooler. Rainfall will probably increase worldwide, but some regions may become drier as climatic belts shift poleward. Growing seasons in temperate zones will be extended. Productivity of agriculture, forestry, and other biological resources will be increased in some regions, and reduced in others.

The urgency of research on biological effects of CO_2 increases arises from the potential for both good and harm. We need to learn how to exploit the potential benefits, and alleviate adverse effects. There is also a need to plan for societal and institutional responses to biological change. Finally, we need to point the way to the future, even if there can be no organized response.

A particularly vulnerable area of the world is the tropics. Highly populated less-developed countries in both the semi-arid tropics and regions with abundant rainfall often have marginal agricultural systems. CO_2-induced temperature increases will probably not result in a significant decline in agricultural production in equatorial regions. Many countries, however, are already marginal in precipitation, and major shifts in rainfall patterns could have either important detrimental or beneficial effects on food production. Research should pay special attention to the needs of the Third World. (For a further discussion, see paper by Lloyd Slater, Volume II.)

Recommendations for research fall into three broad categories: direct biological effects of increased atmospheric CO_2 on plants; climatic effects on cultivated agriculture; and climatic impacts on noncultivated renewable resources. There is no sharp division in research opportunities among these categories, particularly the last two.

A. Direct Biological Effects of Increased Atmospheric CO2 on Plants

There are major questions about the direct biological effects of elevated levels of atmospheric CO_2 on agricultural crops, pests, forests, marine and freshwater plants (see also Marine Biota, Section I), rangelands species, and microorganisms. The wide-ranging impacts of the CO_2 phenomenon makes it an issue of global significance. It relates directly to optimization of the productivity of agriculture, rangelands, and forests and fisheries -- all renewable resources.

Current research on the direct effects of CO_2 on plant life is wholly inadequate; a major new research program must be initiated. This program should address topics such as the fertilization effects of elevated levels of atmospheric CO_2 under field conditions; the effects on photosynthesis, biomass production, yield, harvest index, crop maturity, and water-use efficiency. The response of plants exposed to higher levels of CO_2 in combination with different kinds of stresses should receive special attention. These stresses include those caused by air pollution, moisture deficiencies, temperatures, mineral nutrient deficiencies, and pests. Research should consider three principal questions: 1) How will biological processes such as photosynthesis, nitrogen fixation, transpiration, and reproductive development respond to a unidirectional increase in atmospheric CO_2? 2) Can genetic types be developed to take better advantage of CO_2 fertilization? And 3) How can management practices be altered to make use of higher concentrations of atmospheric CO_2? Also important is the extent to which the composition of multispecies noncultivated ecosystems will change significantly in response to the differential effects of CO_2 fertilization.

An integrated research program to study the direct biological effects of rising CO_2 levels on plants could take between 10 and 20 years. Scientists representing a wide variety of disciplines should be involved from the beginning in planning the program and in selection of specific research projects. These scientists should come both from industrialized and less-developed countries. It is recommended as a top priority that an international conference be held as the first step in planning the overall program.

During the program's planning stages, however, limited specific research programs should be undertaken. These would determine the responses of genetic variants of food, forest, range, weed species, and water species both to elevated levels of CO_2 and to different environmental stresses.

PRIORITY RESEARCH:

o International Conference on the Biological Effects of CO2 on Plants. The U.S. Department of Energy, in collaboration with other concerned agencies and organizations, should sponsor a working conference with approximately 200 participating scientists to establish research imperatives and recommendations for a program dealing with the direct biological effects of elevated CO2 levels on plant life. Among the participants, to be drawn from many countries, should be crop-production scientists, foresters, ecologists, microbiologists, marine biologists, plant physiologists, biochemists, engineers, specialists in plant protection, sociologists, economists, anthropologists, and political scientists. Seven or eight working groups should be established dealing with marine biota, grazinglands and range, forest ecosystems and productivity, freshwater ecosystems, soil microbiology, agricultural productivity, water-use efficiency, and weeds. The water-use efficiency group might be combined with the one on agricultural productivity. Special attention should be given to the vulnerabilities of agricultural crops in Third World countries.

Chairmen or co-chairmen of the working groups (probably scientists already conducting research on CO2 effects) together with a conference steering committee, should select conference participants and members of working groups. The commissioned papers (Volume II) might serve as initial working documents for the working groups.

The conference should last five days, with an agenda of working group and plenary sessions. Rapporteurs should be identified for each working group and there should be an editor for the conference proceedings or some other kind of report of the meeting. The proceedings, along with a precise listing of recommendations for high-priority research projects, methodologies, and recommended funding levels, should be published within three months of the conference. Expenses of participants should be covered, with honoraria to chairmen of the working groups and a few other key participants.

OTHER PRIORITY RESEARCH

o Differential Responses of Plant Variants. Studies should be funded of differential biological responses (photosynthesis, nitrogen fixation where applicable, transpiration, reproductive development, translocation, harvest index) to high levels of $CO2$ on genetic variants of major food, forest, range, and weed species. These responses should include experiments with seedlings in controlled environments. Food-crop groups to be studied should include: wheat, barley, rice, maize, sorghum, soybeans, potato, sweet potato, peanuts, bananas, and cassava. The major forest species to be examined should be Douglas fir (Pacific Northwest), loblolly pine (Southeast), aspen (Lake States), eucalyptus, and a variety of fast growing trees with symbiotic nirogen-fixing bacteria, such as Casuarina, Acacia, Leucaena and Sesbania (tropics), and Norway spruce or beech (Europe). Major weed species should be represented by purslane, red root pigweed, and Johnson and quack grasses. (See paper by D.N. Baker, L.H. Allen, Jr., and J.R. Lambert, Volume II.)

o Plants, CO2, and Environmental Stresses. An inventory of the responses of major food, forest, range, and weed species grown under conditions of high CO2, coupled with environmental stresses including air pollutants, nutrient-poor soils, deleterious concentrations of toxic elements or excess salt, moisture deficiencies, and high temperatures is an important research project. Initial research should be performed on seedlings grown in controlled environments. This work should be followed by research on whole life cycles. Studies on the major agricultural forestry and food crops should be given priority. Agricultural crops would include rice, wheat, maize, potato, sorghum, soybeans, cotton, sweet potatoes, cassava, and sugar crops. Equally important are studies on the major forest species, Douglas fir, loblolly pine, poplar, eucalyptus, Acacia, Casuarina, Leucaena, Norway spruce, and beech. The research should be coordinated closely with the research suggestions dealing with alleviation of environmental stresses on renewable resource productivity. (See paper by Gordon S. Howell, Volume II.)

o Water-Use Efficiencies. We need to determine how water-use efficiencies of plants are modified under various levels of atmospheric CO2. Selected C_3 and C_4* food crops, forest tree species,

*C_3 and C_4 refer to alternative genetically determined biochemical pathways of CO2 assimilation in photosynthesis. Plants having these different metabolic pathways tend to have different responses to CO2, light, and other environmental factors. A third pathway, called CAM, occurs in some succulent plants. C_3 plants, in general, show a marked response to elevated levels of atmospheric CO2.

and range and weed species should be used in the experiments. Crop water-use efficiency can have a major impact on agricultural growing seasons. This is particularly true in the tropics and subtropics. Work in this area should be closely related to research on growing seasons. (See paper by James Newman, Volume II.)

o Microbiota and Microorganisms. Studies should be performed on the effects of elevated atmospheric CO_2 levels on soil and water microorganisms. Initial research should focus on mycorrhizae and the biological nitrogen fixers (Rhizobia, actinomycetes, Spirillum, Anabaena). These organisms should be studied in combination with their host species.

[The above four research areas should be carefully coordinated. Tactical details of the research effort must be defined by research specialists submitting formal proposals. Results of these preliminary or initial studies would provide a partial data base for the international working conference recommended above.]

o Response of Noncultivated Ecosystems to CO_2 Enrichment. Agricultural crops in the U.S. and some other industrialized countries are managed primarily as monocultures. Hence all individuals in a stand will respond similarly to CO_2 fertilization, although some genetic variants may be favored. Noncultivated ecosystems, with their many species, may respond differently to CO_2. Early-growing, cool-season plants are generally more responsive than those species which make their primary growth in summer. The atmospheric concentration of CO_2 differentially affects seedling emergence among species. These differential responses may lead to changes in species composition in forest and rangelands. This could in turn lead to changes in wildlife abundance. We also need to determine the levels of ambient CO_2 under field conditions. Exactly what levels are plants responding to now? Do these levels differ for different regions? What are the levels of atmospheric CO_2 over the U.S. corn and wheat belts during early summer, or, for example, of the Amazon basin in the tropics?

Multispecies interactions are only partly amenable to laboratory research. There will have to be heavy reliance on ecosystem simulation models and field studies of ecosystems. The same approaches will be needed for predicting responses of noncultivated ecosystems to climate change. Ecosystem studies to assess potential effects of climatic change should explicitly consider direct effects of CO_2 enhancement on species composition and other ecological characteristics. (See paper by Boyd Strain, Volume II.)

o Stimulation of Aquatic Productivity by Additional CO_2. Even less is known of stimulation of aquatic productivity by increases in dissolved CO_2, than of CO_2 stimulation of crop plants. There is a controversy whether carbon or phosphorus is the primary limiting nutrient in aquatic systems. Water hyacinths, however, have shown a 40 percent increase in production from atmospheric CO_2 of 1000 ppm. Rice is also very responsive. There is no single answer. If there is significant stimulation of aquatic productivity from CO_2 increase there could be substantial economic gains from enhanced fish production (and the possibility of some losses because of increased lake eutrophication).

The literature on stimulation of agricultural productivity by enhanced CO_2 is not matched by similar quantitative studies of freshwater plankton and macrophytes. The confounding effects of pH change and carbonate water chemistry are poorly known. This information is necessary for accurate predictions of aquatic fixation of carbon as atmospheric CO_2 increases.

If most aquatic production is phosphate limited, the impact of increased CO_2 may be minor. On the other hand, anthropogenic nutrients may be expected to increase in the future, perhaps leading to carbon limitation in many waters. Lake surveys such as the National Eutrophication Network should be scrutinized for incipient carbon limitations. Laboratory and controlled ecosystem research is needed to quantify the production increases that could be expected from enrichment of air with CO_2. Experiments should be conducted with various levels of phosphorus to approximate natural waters. Laboratory studies of CO_2 enrichment at different levels of nutrients and other factors, followed by larger-scale pond or channel studies, would appear to be a desirable quantitative approach. Modelling of aquatic production should be used to elucidate the role of carbon availability in aquatic production. (See paper by Charles Coutant, Volume II.)

Biological Monitoring

Modelling enables prediction of the consequences of climate change on ecosystems. Biological monitoring, on the other hand, permits the evaluation of model predictions and identification of biological responses to climate change. Carefully planned monitoring experiments are no less important for understanding the implications of rising CO_2 levels than well-designed mathematical models or field research.

Much of the needed monitoring for biogeographical research can be performed by utilizing and strengthening existing networks, including UNESCO's Biosphere Reserves Program, the U.S. Forest Service's Continuous Forest Inventory (CFI) program, and the national resource lands inventory program administered by the U.S. Bureau of Land Management. CFI data, for example, have been used to assess the state of forests vis-a-vis timber products. The trend toward multi-resource inventories is making CFI data increasingly valuable for general ecological monitoring that can be used in addressing CO_2-induced climate effects.

PRIORITY RESEARCH

o Monitoring Program. A hierarchical program should be established to monitor the biological effects of increasing levels of atmospheric carbon dioxide on ecosystems. The program would rely on the Forest Service's Continuous Forest Inventory and the Bureau of Land Management's inventory of natural resources to establish general levels. The intermediate level would consist of UNESCO's Biosphere Reserves Program. And the final level of the monitoring program would consist of sites at forest ecotones and core regions specially chosen to study relationships between forests and climatic changes. Implementing this program may require interagency coordination stimulated by the Department of Energy.

B. Climatic Effects on Cultivated Agricultural Growing Seasons

Climatic warming caused by increasing amounts of atmospheric CO_2 could have large effects on the growing seasons of crop and forest species. If this occurs, it could cause dislocations in agriculture and forestry in many regions of the world. In the United States, for example, it has been estimated that for each 1°C temperature rise, the corn belt would shift approximately 175 kilometers northeast. Similar dislocations could affect most major food and oil-seed crops and commercial forest species. For many crop regions, the length of the frost-free growing season or the period with temperatures above some minimum are at least as important as the seasonal mean temperature.

PRIORITY RESEARCH:

o Agricultural Growing Seasons and Climate Change. Using historic climate data, an assessment should be made of expected effects of climate change on agricultural growing seasons in temperate and tropical, semi-arid and humid, and developed and less-developed regions. Modelling techniques should be developed to simulate changes in growing seasons for various grain-belt areas and range and forest regions. Simulations should be based on a range of estimated temperature and precipitation changes in particular regions because of increasing CO_2 levels. Areas to receive particular attention should be the corn and soybean belt and winter wheat belt in North America, African and South American tropical rangelands, and tropical rain forests. (Temperature changes in the tropics are expected to be less than at higher latitudes.) The effects on major food, grain, oil-seed, and specialty crops representing both C_3 and C_4 types should be studied. The assessment should give particular attention to possible shifts in boundaries of crop regions, with their implication for social change. (See paper by James Newman, Volume II.)

Alleviation of Environmental Stress on Renewable Resource Productivity

Rising levels of atmospheric CO_2 and accompanying projected climate changes will induce environmental stress in many plants. Also, plants vary greatly in their responsiveness to CO_2 fertilization. This will likely result in favoring some at the expense of others. Warmer temperatures, more or less rainfall, and changes in soil nutrients, at all levels, will produce stress. Plants have always encountered climatic stress, but now for the first time the stresses, both biological and environmental, are expected to be worldwide and unidirectional.

Research on alleviation of climate stress for food and fiber crops and other renewable resource production such as forests and rangelands is important whether a CO_2-induced climate change occurs or not. Unfortunately, little research is currently being supported on stress physiology of renewable resources. This is particularly true in the semi-arid tropics of many less-developed countries. Research on alleviation of climatic stress is also lacking in developed countries with advanced research establishments. In the United States, research on stress physiology is now excluded from the Department of Agriculture's competitive grant program in plant and animal resources.

The significance of the impact of climatic stress on agricultural crop production induced by higher than normal temperatures accompanied by a lack of rainfall was manifested during the summer of 1980 in much of the U.S. corn belt, the Mississippi Delta and Texas and Arkansas. The composite index of crop yields fell by 18 percent with production sharply down from 1979 levels for corn, sorghum, soybeans, feed grains and potatoes.

Heat and water stresses are the chief concern, but low temperature stress is also important. Atmospheric pollutants, especially oxidants, are also an increasingly serious source of stress. Particularly important is the interaction of these pollutants with heat, moisture, and CO_2 fertilization. Stresses from unfavorable soil and nutrient levels, and alkalinity and excess salts, could also be increased through climate change.

There are two principal ways to reduce environmental stress in crop productivity -- genetic improvement which results in greater adaptability, and crop management techniques which make best use of the genetic potential. Research aimed at partially alleviating the crop-yield reduction from environmental stress needs to proceed in parallel along three lines: 1) expansion of the knowledge base; 2) breeding for adaptation to temperature, water, soil nutrients, and oxidant stresses; and 3) development of production management systems which maximize genotypic resistance to environmental stress. (See paper by Gordon S. Howell, Volume II.)

PRIORITY RESEARCH (in order of importance):

- Basic Biology of Plant Response and Resistance to Environmental Stresses. There is an ongoing need for research on the fundamental mechanisms by which environmental stresses disadvantage some plants while other plants can tolerate such stresses. An understanding of these mechanisms, their costs, and how they function must be developed. It is important that the interactions of CO_2 with stress be studied in detail. Will rising levels of CO_2 help counteract the effects of oxidants and other air pollutants? What is the precise relationship between the results of CO_2 fertilization and the effects of moisture or nutrient stress? Research in this field should proceed at all levels, from biochemical to whole-plant responses.

  Important to this effort is improvement in measurements -- both local and area-wide -- of moisture status in the plant and soil. The availability of such a capability is essential to evaluate the multiple impacts of alterations in temperature and rainfall. Recent advances in the use of microwave and infrared sensing at various heights from the ground to satellites, have revealed a great potential for more precise measurements of soil moisture stresses. Much additional work with emphasis on the objectives and needs of the CO_2 research program should be initiated. Techniques and instrumentation requirements should be emphasized.

There are critical stages, such as during flowering and seed formation, in the development of all plants when they are particularly sensitive to moisture, and high- and low-temperature stresses. (There may be similar sensitivities to elevated levels of atmospheric CO_2.) Agronomic, horticultural, and forest specialists should endeavor to define these periods, evaluate their sensitivity to varying degrees and duration of stress, and assess the physiological and yield impacts.

- Genetic Manipulation to Improve the Resistance of Crop Plants to Temperature and Water Stresses. A great potential exists within the germ plasm pool of economically important species for characteristics that strengthen plant resistance to extremes of water and temperature stress. Major food crops, such as maize, potatoes, and soybeans, should be selected to: 1) identify the physiological traits of genetic value to stress resistance; 2) develop workable screening tools for use in breeding programs; 3) conduct germ plasm surveys to detect potential parent material with the resistant characteristics; and 4) initiate plant-breeding efforts that incorporate these characteristics into existing breeding lines. (Attention should be directed to development of halophytes -- salt tolerant plants.)

- Broadening the Optimum Productivity Range for Crops. Crop-yield models and climatic probability inputs for temperature and moisture can be effectively used in risk analysis. This will aid in the development of agricultural production systems that minimize year-to-year variation under temperature and moisture stresses. Agriculture has tended to develop crop management systems which maximize yields under ideal climatic conditions. Unfortunately, climatic variability results in highly variable yields with such systems. An analysis is needed of the optimum range of production for agronomic and horticultural crops. The effort should aim at maximizing yields over a relatively long period (e.g., 10 years).

This program should be integrated with social science research programs on ways to speed the adaptation to new technologies and new climatic conditions (see Section III). Particularly pertinent is evaluation of the extent to which farmers in different social and economic settings are "risk averse" or "profit maximizers."

o <u>Special Problems of Woody Perennials</u>. Fruit and nut trees and other cultivated woody perennials have unique problems during climatic shifts because of their longevity in a specific area. The key physiological and structural features of stress resistant species and cultivars should be identified. This will give insight to potential impacts of temperature and moisture stress and how to manage these systems to modify or even take advantage of climatic shifts. The environmental preconditioning responsible for cold or heat adaptability should also be determined. This research would also be relevant to managed forests.

<u>CO2-Induced Climate Change and Its Effects on Plant Protection</u>

Plant pests -- weeds, insects, nematodes, and plant diseases -- inflict substantial losses on the world's major food crops, forests, and rangelands. Many pests will quickly adapt to CO2-induced climate changes, especially to those changes that result in higher temperatures. Other pests that may thrive under changing climatic conditions include those that are particularly noxious to people and livestock. These may include fire ants, and many insects that spread human and animal diseases. (See paper by Dean Haynes, Volume II.)

Many pests are currently developing resistance to chemical pesticides and other pest-management techniques. This emphasizes the importance of research on how to control pests in a high-CO2 world. Among the more promising research areas are those involving integrated pest management techniques.

PRIORITY RESEARCH (in order of importance):

o Weed Changes in Crop Competition. Some of the world's most noxious weeds -- purslane (CAM and C_4), red root pigweed (C_3), Johnson grass (C_4), and quack grass (C_3) -- will respond differentially to CO2, both photosynthetically and climatically. A specific example is purslane. Globally it is the fourth most abundant noxious weed. It is a succulent responsive to high temperatures and may alternate its photosynthetic pathway from CAM to C_4. A research project should study the responses of these four weed species to varying levels of atmospheric CO_2 and temperature. This research will take about five years.

o Plant Diseases Which Utilize Stomatal Openings for Penetration and Emergence. Some of the most serious plant diseases caused by fungi, such as wheat rusts, mildew, and potato late blight, enter only through the leaf stomata, or through the leaf cuticle and then sporulate in the stomata. Some particulate atmospheric pollutants also enter or may clog stomates. Little is known regarding the impact of high CO_2 on stomatal behavior and disease entry. Researchers should screen world literature for temperature impacts on sporulation and penetration of diseases through or in stomata. Three major crops should be studied: wheat, potato, and rice.

o CO_2 and Hydrilla verticulata. Hydrilla is rapidly becoming the world's most widely distributed aquatic weed. It blocks irrigation canals and dominates many lakes, rivers, and ponds. It acts almost as an aquatic purslane. Dense Hydrilla can exhaust the soluble CO_2 in shallow waters within less than half a day, leaving a CO_2-starved environment. Much more information is needed as to the direct effects of CO_2 on this weed. Also, some northern lakes are being partially sterilized by acid rainfall. Weeds like Hydrilla could migrate northward (or southward) with a global warming. Both the physiological effects of CO_2 and climatic effects in the growth and distribution of Hydrilla need study.

o Insect and Nematode Pests. Research to aid in management and control of these pests in the face of expected climatic changes should emphasize both theoretical and modelling studies and empirical field observations.

Using existing data and models of cereal leaf beetle and fall webworm populations, research should couple a physical climate model with a biological pest model. This simulation model could then be generalized for a wide range of other pests.

The concept of an economic threshold is critical for decisions on pest-management programs. It would be important to predict pest damage under increasing CO_2 levels so that decisions can be made on how and when to protect against particular pests. The objective will be to expand the economic threshold concept of integrated control techniques so that simulations can be run with variable climatic conditions, such as rising temperatures. The research should be validated with two selected crop systems.

Many crop pests are likely to be significantly affected by climate change. For example, there should be an evaluation of the effects of elevated spring and fall temperatures on the growth and development of cutworms and armyworms, pests that are particularly harmful to conservation-tilled corn and wheat. High fall temperatures greatly increase the size of the overwintering army worms and high spring temperatures may produce additional generations.

Root-knot nematodes are another example. They are among the 10 most significant pests of food and fiber crops. This group causes 90 percent of all nematode damage in the world. The geographical distribution of many species is limited by temperature. Root-knot nematode problems are most severe in warm climates. The temperature requirements to increase the number of generations of species of this nematode by one generation per year should be determined. One can then assess the impact of a CO_2-induced temperature increase on the significance of root-knot nematodes as pests.

The fire ant, an exotic pest, is now distributed as far north as North Carolina and as far west as Lubbock, Texas. Its distribution is temperature-dependent. A project should explore the impact of projected CO_2-induced temperature changes on the distribution and abundance of fire ants. The project should use existing population-dynamics data to develop a simulation model which would determine how the range of fire ants might shift under higher temperature regimes. Other species of ants would also be good indicators of climate change. This project should bring together biologists and climate modellers, a collaboration that should prove extremely useful.

Agriculture in Developing Countries

Many of the world's less-developed countries are in the tropics or subtropics. Although climate change from increased atmospheric CO_2 is expected to be less than in temperate latitudes, special problems and opportunities will likely be associated with those changes. High temperatures in a tropical setting permit multiple cropping, providing water is not limiting. Relatively slight climatic shifts may increase or decrease possibilities for multiple cropping.

Irrigation can alleviate climate stress from a lack of water. Climate change may, however, alter the quantity of water available from existing and planned irrigation systems. Research to develop better site-specific irrigation techniques and to transfer these techniques to farmers could extend the water supply and increase agricultural production in the tropics.

Multiple cropping of land, aquatic polycropping with a variety of species, and management practices resulting in agricultural diversification can be a buffer against climate change as well as a means of increasing production. New combinations of crops and cultural practices should be designed so they are compatible with each other and utilize the latest inputs from plant breeding (including halophytes), plant protection, tillage, soil and water management, and other research areas. There should be research on animal production, including fish-farming (aquaculture), in which crop by-products are fed to animals and the animal by-products recycled to provide plant nutrients.

Tree crops and other perennials are generally more tolerant of climatic variability than annuals. Agroforestry -- a production system which endeavors to optimize production by combining tree perennials with other plants or animals on the same unit of land -- is one of the most promising types of multiple cropping in developing countries. It may help to meet growing demands for food, fiber, and firewood. Agroforestry mimics the natural forest ecosystem in preventing loss of soil fertility from leaching and erosion. This is especially important in developing countries, where soils are predominantly poor and vulnerable. Research in agroforestry requires an integrated approach; interactions among different plant species are often site-specific, making it difficult to generalize. Another constraint is that we now know only a few tropical perennials which can be recommended for commercial planting and to improve the economic conditions of rural populations in the tropics. (See paper by Lloyd Slater, Volume II.)

PRIORITY RESEARCH

- Productivity and Resilience of Tropical Agriculture. Research to improve agricultural productivity in the tropics and subtropics is urgently needed to help feed the world's growing population, whether or not significant climate change occurs. This research should be accelerated, with increased assistance from the industrialized world. Tropical agricultural research must take account of the social and institutional structure in each locality, as well as biological resources and management techniques. It is important that agricultural research in the tropics and subtropics be planned to take explicit account of the possibility of climate change. It should also take advantage of the expected increase in atmospheric CO_2 as it relates directly to the biological processes of photosynthesis, biological nitrogen fixation, and transpiration that control plant growth.

Effects of a CO_2-Induced Climate Change on Animal Agriculture

Domestic animals provide high-quality protein, minerals, vitamins, and energy for human consumption. Meat, milk, eggs, and wool account for approximately 40 percent of the world's agricultural output, and many cultures in the world depend almost entirely on animals for their food supply and much of their fuel and draft power.

The importance of research in this area transcends the CO_2 issue. It is of both national and international concern. An increase in ambient temperature will generally reduce total productive efficiency of most livestock. Extremely high temperatures can result in high casualty losses, as witnessed in 1980 with poultry in Texas and Arkansas. CO_2-induced temperature changes impact directly on animal physiology as well as indirectly on forage production, soils, and animal diseases. Coping with ambient temperatures is the basic issue. The proposed research includes highly detailed basic physiological and biochemical studies of animals in environmentally controlled chambers, as well as studies of animals managed under extensive grazing conditions. Testing of management systems, including computer modelling and analysis, is recommended.

The objective of this research area should be: 1) Determine the effects of thermal stress on nutrient metabolism, hormones, and diseases associated with growth, reproduction, and lactation of animals; and 2) develop systems of management which increase efficiency and productivity of animals exposed to thermal stress.

Research on the partial alleviation of CO_2-induced climatic stresses on livestock is particularly crucial in that large projected temperature changes will occur in the temperate zones where there is the greatest concentration of climatically vulnerable animal agriculture. The temperature change and resultant stresses will be less in the tropics and in developing countries. In these areas the projected climate changes will be minimal, and water buffalo, the prodominant species, is already well adapted.

Animal agricultural research is expensive in terms of capital outlay, facilities, equipment, and animals. The research program outlined below will require extensive use of research-farm and laboratory facilities, as well as controlled environmental chambers for large and small domestic animals. The proposed research should not necessarily be confined to carbon dioxide-climate effects alone. (See paper by H. Allen Tucker, Volume II.)

PRIORITY RESEARCH (in order of importance):

o Establish the Quantitative Effects of Thermal Stress on Nutrient Requirements, Feed Intake, and Nutrient Utilization of Selected Animals (Beef and Dairy Cattle, Swine and Poultry) Managed Intensively and Extensively. The nutrients (amino acids, vitamins, minerals, and calories) required by food-producing animals have been qualitatively defined and, so far as is known, do not change with ambient temperature. Quantitative nutrient requirements were established under ideal conditions, but most animals are not managed under ideal conditions. Since heat stress reduces voluntary feed intake, quantitative requirements for many nutrients may not be met during thermal stress because nutrients are fed as a percentage of dietary dry matter. Quantitative requirements and the relative ratios of various nutrients (e.g., protein-to-S, protein-to-energy, K-to-Na, etc.) are likely to be markedly different during thermal stress.

The research should : a) describe nutrient flux (including nutrient utilization) and productivity of animals exposed to variable temperatures for various times (these data should be applied to determine nutrient requirements); and b) determine the accurate quantitative relationships between feed intake and ambient temperature for selected animals.

This research should be conducted in both controlled environment chambers and under monitored field conditions.

o Determine the Effects of Thermal Stress on Endocrine, Physiological, and Biochemical Factors Which Regulate Growth, Reproduction, and Lactation. Hormones are biological agents secreted in animals which regulate meat, milk, and egg production. These effects are manifested throughout an animal's reproductive system. Thermal stress reduces growth, reproductive, and lactational performance of animals, and causes shifts in secretion of some hormones. We do not as yet understand the endocrine system in sufficient detail to permit its manipulation to reduce thermal stress.

Higher temperatures decrease ovulation rates, reduce the intensity and shorten the duration of estrus, and increase embryonic mortality. The mechanisms of these responses are poorly understood. There is a hypothesis that, in addition to hormones, other biochemical and physiological factors may be involved. The response to thermal stress is not sufficiently understood to allow development of practical management systems to reduce it.

The effects of various intensities and durations of thermal stress on secretion rates of hormones from endocrine glands and the clearance rates, patterns of release, and molecular forms of hormones in blood should be determined. Studies should be restricted to those hormones which are known to regulate growth, reproduction, and lactation. There should also be a determination of the effects of heat stress on physiological and/or biochemical factors which control fertility of gametes, embryo and fetal survival, conceptus-maternal interactions, neonatal growth, postpartum reproductive physiology, and lactogenesis.

This research may involve use of environmentally controlled chambers using relatively few numbers of animals very intensively. Research could also be conducted under "normally fluctuating" temperatures and other climatic variables. The latter approach is especially useful where large numbers of animals are required to determine the effects of thermal stress on growth, reproduction, or lactation.

o <u>Determine the Effects of Thermal Stress on Diseases Which Affect Animal Productivity.</u> Many diseases reduce animal productivity, and climatic stress may exacerbate the problem. The influence of climate, particularly the effects of thermal stress, on transmission of infectious agents is not completely understood. There is need for managerial systems which can be applied to the husbandry of animals that will prevent transmission of infectious agents to animals subject to CO_2-induced climate changes.

Research should: a) define the ways in which climatic factors affect survival, development, and movement of infectious agents in the environment; and b) determine systems of animal management which minimize disease during thermal stress.

This research will require closely regulated environments as well as environmentally monitored field studies.

o <u>Develop Systems of Management Which Increase Efficiency and Productivity of Animals Exposed to Climatic Stress.</u> Potentially practical management systems to alleviate thermal stress on animals could be tested immediately. They may include, but are not limited to: 1) testing applicability of the managerial system of "least-cost programming" for normal dietary formulations to development of dietary formulations for animals subjected to thermal stress; 2) testing the performance of animals whose dietary formulations were altered based on recently developed correlations between feed intake and ambient temperature; 3) developing management strategies which synchronize breeding periods with periods most favorable to conception and reproduction; and 4) developing low-cost animal shelters which will buffer climate changes. In addition, computer modelling and analyses in response to changes in climate could be used to predict: 1) the extent of the changes in animal productivity; 2) choices among animal production systems; 3) marketing and food consumption patterns; and 4) cost/benefit ratios. This research will require extensive use of computer facilities and field testing of computer simulations.

C. Climatic Impact on Noncultivated Renewable Resources

Biological processes in a forest do not differ from those in a wheat field. The distinction between cultivated and noncultivated ecosystems is in the degree of human intervention. Lower returns per unit area, a preponderance of long-lived perennial species, and often quite different management objectives mean that most natural resource systems are treated less intensively than agricultural crops. Because of this lesser human control, their response to climate change will be qualitatively different from that of agricultural systems. In particular, changes in species composition will be more the result of natural processes than of human choice.

The relatively low level of manipulation affordable in natural resource systems means that there is less opportunity than in agriculture for economic benefit from climate change. The main objective of research on noncultivated ecosystems should be to anticipate responses of ecosystems to new climates. Unexpected changes could be costly. Believable scenarios, though, can be worked out to indicate how natural resource systems may react to climate change. Management practices may then be adjusted to take advantage of the shift or to minimize its adverse consequences.

Research on impacts of climate change on noncultivated ecosystems should concentrate initially on processes and models. Many of the expected responses will be highly site-specific, and cannot be properly assessed until there are good predictions of local climate change. The processes that will lead to ecological change, however, are more universal.

Shifts in climate will affect forests, grazinglands, water resources and freshwater ecosystems, and terrestrial wildlife. Research should consider the effect of CO_2-induced climate change on recreational and aesthetic, as well as economic, values. In addition, there should be a continuing program of biological monitoring to detect ecological trends as they occur.

Impact of Climate Change on Forests

About a quarter of the U.S. is covered by forests. These range from a small but growing area that is intensively managed under high-yield silviculture (scarcely differing from agricultural cultivation) to sparse and unproductive woodlands. There are extensive forests throughout the world. Those in some developing countries are already under severe stress from overcutting and heavy grazing. These stresses may be exacerbated by climate change.

Most forests are managed for direct economic return, but some are set aside as parks or wilderness areas where harvest is forbidden. Almost all have high recreational value. Effects of climate change will differ according to management practices and ecological characteristics.

A substantial share of the world's research in both theoretical and applied ecology has been conducted in forests. Despite the excellent data on which to build, the ability of ecologists and foresters to predict consequences to forest ecosystems of a CO_2-induced climate change is poor. Basic research and model synthesis and development will be necessary before accurate predictions can be made.

Research concerning CO_2 effects on forests can be divided into five areas: mathematical modelling; species tolerance and genetic adaptation; adaptive strategies for managed forests; land-use shifts; and field sites for research. All these areas should be considered in an integrated research program. (See papers by Larry Tombaugh, and by Carter Johnson and David Sharpe, Volume II.)

PRIORITY RESEARCH:

- Mathematical Modelling. Priority should be given to the development of mathematical models of forests which include both population and ecosystem processes. This hybridization of population and ecosystem models is vital to predicting the consequences of a climate change. A CO_2-induced climate change would affect both population dynamics and rates of ecosystem processes. Few mathematical models have been designed to evaluate both components simultaneously. There is also a need to incorporate climate as an operational variable. This will require explicit linkages between the components of changing climate and ecosystem-population dynamics. Most mathematical models of ecosystems have been structured to evaluate relationships between and among functional biological categories under a constant climate but with year to year variations. Few models are designed to evaluate the effects of a unidirectional climate change. Full evaluation of climate change will require increased emphasis on spatio-geographic modelling, in contrast to point-scale modelling. This includes prediction of potential shifts in species ranges and faunal migration patterns. A challenge in this area of ecological modelling is to incorporate adequately the effects of anthropogenic activities. Recent land-use practices have reduced the migration potential of some species and enhanced others. The possibility of climate change has added new relevance to the study of biogeography, especially the role of spatial heterogeneity to movement and establishment of populations and communities.

o <u>Species Tolerance and Genetic Adaptation</u>. Prediction of changes in the geographical ranges of species depends on knowledge of the tolerance of different life stages of organisms to a given change in climate. The range of a species can shift if climate change enables colonization of new sites beyond the normal range and if mortality in a portion of the range occurs from changes which exceed the tolerances of all individuals of local populations. Complete mortality of range-border populations depends on the rate and magnitude of a climate change and on inherent genetic heterogeneity. Some individuals may persist and subsequently increase in numbers. The ability of the species to respond in this way depends in large measure on the genetic variability inherent in the population. Evaluation of the ability of ecotypes and subspecies to persist geographically in spite of a climate change, due to inherent genetic heterogeneity in tolerance, is an important research area.

o <u>Development of Genotypes and Management Strategies for Environmental Stresses in Managed Forests</u>. CO_2-induced climatic shifts may affect the productivity of forests and alter their susceptibility to natural disasters such as fire, windstorms, and floods, as well as to pathogens and insect outbreaks. These problems are particularly important in forests because, unlike annual crops, they take so long to develop that significant climate changes may take place during their lifespans. To develop strategies for optimum management of forests under changed and changing climates will require: a) better knowledge of climatic effects on forest growth and hydrology; b) new tools for assessing changes in forest biomass and productivity through remote sensing; c) models developed from existing knowledge and new research which can be used to develop management strategies optimized for conditions which do not yet exist but which can be expected to occur before trees presently being planted are harvested; and d) development of new genotypes of forest trees able to grow under the changes induced by increases in atmospheric CO_2.

o <u>Land-Use Shifts.</u>* An indirect effect of climate change on ecosystems occurs through man's use of the land. Land use plays a role in ecosystem dynamics in most regions of the world, through clearing and reforestation, conversion of grazingland to agriculture, farm abandonment, and grazing and utilization practices. At issue is the effect of changing climates on land-use patterns. If climate becomes more favorable for agriculture and intensive forestry, and this is coupled with economic incentives, land that is currently under natural vegetation and marginal for agriculture could be cleared. Conversely, if less favorable climates result, extensive agricultural land abandonment could ensue. This problem is most critical in marginal agricultural regions impaired by constraints of temperature or moisture. Land use and water use in irrigated agriculture go hand in hand. An example is the North American deciduous-boreal coniferous forest ecotone. A warming could expand agriculture at the expense of natural systems -- for example, the western margin of dryland agriculture on the Great Plains. How is land and water use likely to change in such sensitive regions? Will agricultural land increase

---

*This issue cuts across many other important research topics discussed in this report -- agriculture, forestry, grazinglands, and economics and other social science research. Care should be taken to coordinate such research efforts wherever possible.

or decrease? What will be the speed of change, and what portions of the landscape are most likely to be affected?

Rates of change in land use are a response to a complex interplay of climatic, economic, social, and demographic factors. Elucidating the mechanisms by which these rates could be altered by CO_2-induced climate change will require a high degree of interdisciplinarity involving cooperation among biological and social scientists. Research should emphasize the mechanisms involved, with the aim of developing a statistical basis for predicting future landscape patterns resulting from the interplay of climate and social forces. It is premature, however, given our present state of knowledge, to attempt to predict actual changes in land use in specific regions as a consequence of climate change.

Remote sensing is a potentially powerful tool for evaluating land use changes. A workshop convened at Woods Hole, Massachusetts, May 1979*, proposed a five-year program to improve the capability of remote sensing to measure global changes in terrestrial carbon. The workshop considered measuring changes in land use from forest clearing and similar activities. It made no mention of land use changes from climatic shifts. It is strongly recommended that, if the program of research recommended by that workshop is implemented by DoE or other agencies, it include research on how best to measure long-term changes in land use resulting from climate change.

o <u>Field Research Sites</u>. Testing and validation of model prediction requires carefully selected field sites. We recommend that permanent sites be established where landscape-level research can be conducted on effects of CO_2-induced climate changes on forests. General site selection criteria should include: 1) sites at the center of a number of species' ranges within a given forest biome to measure the effect of climate change on nutrient and energy cycles without the confounding effect of population shifts; 2) sites at or beyond the margins of biomes, where populations often exist under stress and where the effects of changing climate on species' ranges (e.g., ability to reproduce) would be most

---

*Woodwell, G.M. (Ed.). 1980. Measurement of climatic changes in terrestrial carbon using remote sensing techniques. U.S. Department of Energy CONF-7905176.

quickly noticed; 3) regions with perturbation-dependent ecosystems where the mix would change significantly because of climate change, including regions now marginal for agriculture and intensive forestry; and 4) landscapes with a history of population-ecosystem research, where ecological relationships have been determined. No single site would meet all criteria. A priority would be sites at the prairie-forest ecotone and the boreal coniferous-deciduous forest ecotone regions of North America. The latter might best be located in Canada.

Population-ecosystem research should be focused at a relatively small number of sites. We recommend support of only a few adequately funded research sites rather than a large number with marginal funding. Highly fragmented funding might prohibit research success at any site. It is important that research on CO2 effects, in this as in other subject areas, be regarded as a program, rather than as a series of independent projects.

[The minimum funding and time period for all priority research regarding forests should be similar to that for the forest biome studies of the International Biological Program (IBP). The organization of research and composition of the research team would differ from the IBP. The proportion of investigators with backgrounds in bioclimatology, forest meteorology, and biogeography should be larger. Also, the locations for research proposed should play a larger role than it did during the IBP. Research planning should be carefully integrated with the Long Term Ecological Research (LTER) program being implemented by NSF.]

Water Resources and Freshwater Ecosystems

The quantity of water from lakes and streams available for agricultural, domestic, and industrial use and for hydropower generation will be directly affected by climate change. Stream runoff, a high proportion of which is from noncultivated ecosystems, is heavily dependent on rainfall and temperature, but is also affected by ground cover, humidity, and insolation.

The amount and the economic importance of water supply resulting from changes in precipitation and temperature are highly site specific. A 10 percent change in annual precipitation in the Colorado River basin will affect the flow of that river differently than will a similar change in the basin of the Mississippi. Equally important, a 10 percent change in mean annual flow of the Colorado will have different social and economic implications than an equivalent change in flow of the Mississippi.

We do not recommend trying to make quantitative predictions of changes in streamflow until more is known about expected climate changes within specific basins. Research is in progress to improve models linking streamflow to annual variations in precipitation, temperature, and other climatic variables. (Ground cover and vegetation is also important.) These models will be useful for evaluating streamflow changes when locally-specific climatic models are improved. Although predictive hydrologic models still need refinement, the need does not warrant support through the CO_2 program. The prospect of change in streamflow should, however, be incorporated into the scenario exercise proposed in Section IV.

Another set of questions immediately amenable to research has to do with the effects of CO_2-induced climate change on freshwater biological resources. The most important of these are changes in species distribution, the impacts of new reservoirs and of reservoir operating policies, and temperature change, on aquatic productivity. (See paper by Charles Coutant, Volume II.) Also important is the export to the marine environment of carbon in rivers, discussed in Section I of this report.

PRIORITY RESEARCH:

- Species Distributions. Recreational fisheries, and some commercial fisheries, often exploit aquatic species at the edges of their latitudinal geographic ranges. Small increases in long-term temperatures can shift distributional boundaries and cause social displeasure at the resource loss. A small rise of average temperatures might allow troublesome exotic fish to spread north to the Florida panhandle and westward across a latitudinal band. Cold-water species in boreal lakes may be threatened by temperature changes. The interaction of temperature change with acid rain in northern lakes may be important. The existing latitudinal boundaries of important aquatic species should be identified, and the role of temperature in maintaining these boundaries established. Laboratory and field data will be required. Evidence may be gained from electric power station sites, particularly where exotic species have been established as a result of increased water temperatures or where native cool-water species have been eliminated. Thermal refuges (locations in the water where species can find their preferred temperature range) in winter or summer should be examined for their influence on distribution and suitability for maintaining desirable stocks with changing temperatures. Climate models should be applied to organism distribution and thermal tolerance maps used to estimate range changes. Range limits should be monitored over time to detect changes. Computerized biogeographic distribution records for birds and mammals may be emulated for aquatic species.

An initial three-year effort can establish distribution maps with existing data. A 10-year project is needed to identify the role of temperature in establishing species ranges.

o <u>Predicting and Planning Environmental Characteristics of New Reservoirs</u>. New water storage reservoirs will be needed to maintain streamflows in many regions if rainfall is diminished or seasonal variability is increased by CO_2-induced climate changes. (Increased precipitation, which is equally likely, could also alter the need for and characteristics of reservoirs.) Expansion of reservoir construction for crop irrigation may be the most socially and environmentally damaging long-term consequence in many regions. There may be trade-offs between food security from crop irrigation and meeting other water needs of people. Until more data are available on the geographic extent and degree of change in water availability, it is not possible to predict where new reservoirs are most likely to be located.

Studies of ecological cycles in existing or new reservoirs and tailwaters (water below a dam or waterpower development) can assist research, assessment, and prediction of physical characteristics and ecological elements of future reservoirs. Current research comparing ecological relationships of different reservoir types and the factors which determine stability or predictability of reservoir community structure, could give more emphasis to the ability to predict ecological relationships based on changes in the physical characteristics of the reservoir. Reservoir studies in the Soviet Union and Africa should be integrated with the U.S. effort, perhaps through the United Nations Environment Program (UNEP). Present knowledge of reservoir systems can be incorporated in engineering designs so as to create habitats for desirable aquatic species and to minimize undesirable components. The facilities needed for this project are similar to those used in ongoing programs in comparative reservoir research and ecological analysis. This research will need limnologists interested in prediction and comparative studies of existing reservoirs, as well as the analysis of results of reservoir studies worldwide. This is a 10 year research program.

o <u>Impact of Temperature Increases on Productivity</u>. There is much concern about the effects of power plant thermal effluents on aquatic systems. This concern has led to regulatory constraints. CO2-induced climate warming could cause temperature changes approaching those by power plants. The available data on effects of temperature rises on aquatic productivity need to be analyzed in the context of a CO2-induced global warming. Much information has been obtained by federal agencies and electric power companies over the past 20 years in response to concerns over thermal pollution. These data may be insufficient for predicting broader impacts. Once deficiencies in existing data are established, additional laboratory and field research may be necessary. Existing and new data should be incorporated into temperature-driven models of aquatic production and decomposition. Existing data bases on thermal effects maintained by government and industry are invaluable resources. Initial analyses of existing data should be accomplished in one year, and then incorporated into production models by the end of a second year. Thereafter, requirements for obtaining new data and incorporating them in the models are highly speculative.

A further question on temperature impacts is: What degree of change in the annual cycle of organic production, oxygen depletion in deep water, and growth of desirable as well as nuisance species occurs with a temperature increase? The hypotheses advanced for power stations regarding the annual cycle need to be evaluated with assumptions regarding wide-scale, CO2-induced temperature change. Comparative studies on aquatic ecosystems at different latitudes may be fruitful. Attention should be given to thermal structure of the water bodies and to nonlinearities in the thermal effects scale, i.e., there may be threshold thermal conditions which induce rapid eutrophication whereas unit thermal changes at lower levels yield no significant changes. Some sites and data already examined by utilities may be utilized to advantage. This should be a long-term research effort, extending at least 10 years.

A final issue involves the changes in trophic condition of major waters that can be expected if nutrient loads are maintained (or increased) but runoff is reduced (or increased) by CO_2-induced climate change. Dynamic models of eutrophication are needed which can estimate the degree of flow reduction (or increase) that will induce eutrophic conditions. Conversely, estimates are needed of nutrient control requirements in order to keep pace with possible changes in streamflow. Any CO_2 stimulation of biological productivity should be included in the models. While little control may be possible of the CO_2-induced precipitation changes, other factors contributing to eutrophication may be managed if estimates of effects are available.

Grazinglands and Wildlife

Range livestock grazing is by definition an extensive form of land use, practiced almost exclusively on land not suitable for intensive agriculture or forestry. It is highly vulnerable to climatic variability.

The questions that should be asked for research on the impact of climate change on grazinglands are not qualitatively different from those related to agricultural and forest lands and animal agriculture. The ecological and socioeconomic setting is different, but the same processes are at work. The same is true of impacts on game and non-game wildlife, which inhabit all these ecosystems. Therefore the strategies for research on impacts of climate change on grazinglands and wildlife should be similar to those already discussed. (See paper by Dennis Pendleton and George Van Dyne, Volume II.)

PRIORITY RESEARCH:

o Rate of Change. Different components of grazingland ecosystems and socioeconomic systems will alter at different rates if climate changes. We expect plants to respond faster than soils. Animals (other than managed livestock, which can be moved) will be a "buffered" system and respond more slowly than plants. What will be the lag response to climate change from, say, the year 2000 to 2050? Assuming a shift from a short to a longer lag response, there might be: 1) decreased or increased annual yield of vegetation and changes in populations of insects; 2) changes in the vegetation composition in terms of shifts of cool-season to warm-season plants on the order of tens of years and changes in populations of rodents, rabbits and hares, and other animal communities within a 10-year time-frame; and 3) changes in economic and social structures in a one-generation interval. These kinds of change should be investigated thoroughly.

o Change in Land Use. What would be needed to maintain productivity given changes in land use induced by changes in climate? Changes in temperature and precipitation would increase or decrease cropland areas or productivity in many areas. With warmer temperatures and less precipitation, forested zones could be converted to croplands to make up any loss in crop production, but generally the soil from such forests is not as high in fertility or as good in cultivation properties as is the soil derived from grasslands. Is the abandonment of croplands closely related to fossil fuel and petrochemical costs to maintain declining productivity? Will these lands be sufficiently degraded prior to abandonment that it will be difficult to recover them into productive grazinglands without requiring high fossil fuel and petrochemical inputs? What will be the relative rate of animal production on abandoned lands undergoing natural secondary succession, as compared to reseeded abandoned lands? These and similar questions deserve research attention.

o Seeding and Succession. Should we rely on natural secondary succession on abandoned croplands or should reseeding be undertaken which may require substantial sources of seed? With a shift of croplands to abandoned lands there will be need for reseeding these lands into grazinglands. Two types of grazingland development may be considered: natural secondary succession in abandoned lands and the seeding of abandoned lands. This defines two major research needs: 1) detailed review and analysis of secondary succession on old-field systems (the rate of succession to perennial grass is dependent on nearby areas of uncropped land for seed); and 2) consideration of the ability of industry to respond to the need for seed.

o Variability of Grazingland Production. Relationships between grazingland production and climatic influences need further examination. The coefficient of interannual variation in precipitation for the southwestern United States is currently about

40-45 percent. The same coefficient of variation is only 30-35 percent in the northern Great Plains. Would increasing temperature and changes in precipitation mean a greater coefficient of variability in precipitation for such a climate zone? The same question could be asked for monsoonal or Mediterranean climatic zones as well as oceanic zones. (At present the global circulation models of future climate regimes with greatly increased CO_2 do not provide detail regarding specific future regional climates.) Variability of economic output on grazinglands is, in part, related to the variability of vegetational yield from year to year. We need to examine the interannual variation in plant and animal production due to climatic fluctuations, beginning with the most productive and/or climatically marginal grazingland types throughout the world.

o Grazingland Animals. Consideration should be given to the type of livestock system available to graze newly derived grazinglands in particular areas as a function of climate change. What is the relationship of domestic vs. wild grazing animals, the relationship of grazers vs. browsers, and the relationship of cool zone vs. temperate zone vs. tropical zone animals to the type of plant communities and climatic systems that may develop in particular regions? Changing climate will not have extreme impact on grazingland animals. There will be less impact probably on wild animals than on domestic animals (though drier or wetter weather might cause shifts in the availability of water which could have serious impacts on wild animals). Research in this area should be integrated with that proposed under the previously discussed topic dealing with animal agriculture.

o Nomadism and Desertification. Climate change may exacerbate (or reduce) the social and biological changes occurring in many parts of the world caused by the intensification of livestock grazing by nomadic herders in semi-arid regions. Research is under way in a number of localities; explicit consideration of the effects of climate change is urged.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

The proposed research on the social and institutional responses to CO_2-induced climate change is based primarily on four questions: 1) What stresses on society would result from the advent or prospect of increasing atmospheric carbon dioxide and associated climate or other environmental impacts? 2) What determines differential vulnerabilities to stress of different social groups? 3) What stress-response capabilities and patterns are presently available in different sectors and at different levels? 4) What response capabilities might be developed for the future?

Since opportunities for direct study of impacts of long-range climate change are limited, the use of appropriate surrogates such as drought, soil erosion, and environmental pollution will be important in the development of an effective research program. These surrogates will give insight into social impacts and behavioral adaptation relative to climate change. Continuous communication among scientists performing the varied research suggested will be essential. Some research by physical and biological scientists may require direct input from researchers studying social impacts or economics, and vice versa. The scenario exercise proposed in Section IV will help lay the groundwork for this type of collaboration.

Research on social impacts and social response to CO_2-induced climate change has unique characteristics that challenge existing research methods and require a skillful blend of the most tried and familiar methods with more exploratory ones. We are dealing in large part with processes of long, slow change. There is little basis for predicting when the indicators of such change will become clear and meaningful signals for the general public, let alone for decision makers or specialists.

In evaluating the social impacts of a long, slow climate change, it is society that is the subject of the research -- not climate. Most social science research on adaptation to change has dealt with short-term, high stress, crisis situations. With regard to CO_2, our need is to understand adaptations around changing long-term climate means rather than short-term extremes of climate change. Nevertheless, slowly evolving changes in climate means (or changes in the range or frequency of extremes) may affect food supplies and water levels as drastically as the more immediate consequences of short-term natural disasters. Thus, the extensive new body of research on natural hazards developed over the last decade may provide valuable information on the different ways in which various groups may be vulnerable to stress and crises. Moreover, some of this new information has implications for long-term behavioral adaptation to changed environments. Theories emerging from this research can contribute to concepts of adaptation to long-term climate change, and need to be thoroughly explored in this context.

The timing of change is a primary consideration. Research should focus on rates of experienced climate (and climate-surrogate) change -- from sudden changes to slow, cumulative ones. It will also be useful to examine experience with cyclical climate change and historical responses to disaster. Attitudes toward the future, practices of futures discounting, and images of hoped for and feared futures are all important determinants of adaptive capacity.

In addition to the more traditional approaches of case history, simulations, and experiments, there is a large area of exploratory research dealing with families, neighborhoods, and special-interest sectors of society. We are aware of the dangers of trying to extract general conclusions from present models of total social systems. To do so could confine us to a level of generality that would preclude important insights concerning interactive effects. Many of the proposed research areas which follow represent efforts to identify and explore the dynamics of significant subsystems within these large categories. Reliable analyses of total systems interactions can only take place when we have much more knowledge of subsystem dynamics at various levels, from the individual to the global social order, and in different sectors -- economic, political, and cultural. See paper by Robert Chen, Volume II.)

Societal Response Units

The societal response units of concern to us are the following:

1) The individual, who processes information and signals concerning change of any kind, who holds attitudes and values concerning society, and who possesses certain skills in relating to society. The biological limits to the individual human being's adaptive capacity under conditions of climate stress will not be dealt with in these proposals, but such studies need to be undertaken jointly with physical, biological and social scientists and should be planned separately.

2) The household, the primary adapting unit in any situation of social change.

3) The local community, which includes the neighborhood and/or village, town, and city.

4) The nation, including both governmental and nongovernmental sectors.

5) The international system, including both formal relations between nations, and private individuals and organizations with international interests and contacts.

Because culture is of primary significance in determining social responses, different types of societies should be examined -- e.g., tribal and national, and industrialized and nonindustrialized. Subgroups defined by gender, age, religion, economic status, and special minority identification should also be taken into account.

Approaches to the Task: Research Areas and Workshops

Because of the unusual nature of the social problems generated by the advent or prospect of CO_2-induced climate change, research organized primarily by conventional disciplinary alignments is not recommended. The proposals which follow fall into eight major interdisciplinary areas. In the absence of any clearly defined relevant body of social science knowledge for dealing with the impacts of climate change, we believe these areas will provide useful points of departure for a long-range research program. As early research efforts make progress, new dimensions of the problem are likely to become evident. These should be either assimilated or blended into the areas delineated here, or else new areas should be added.

The initially proposed research areas are:

1) Development of a climate and society data bank, focusing on periods of climatic stress from the 13th century to the present

2) Historical studies (drawing on the climate-society data bank) of social impacts of climate-induced stresses

3) On-site studies of current climate-stress surrogate situations

4) Identification of social response patterns, focusing on institutional and other response mechanisms in nongovernmental arenas

5) Identification of social response patterns, focusing on governmental arenas

6) Impacts of climate-induced changes (or surrogates) on the international system and the development of international response mechanisms

7) Studies of social perception of long-term climate change and the processing of climate-related information; risk assessment; and decision making

8) Studies of health and disease effects on humans of increased atmospheric CO_2 levels and the resultant climate change

The capabilities of different disciplines, existing knowledge of various topics, and the interdisciplinary integration needed will vary from one research area to the next. Further preparatory work is needed before major research projects can begin, particularly to help social scientists develop some common ground in relation to the problems that must be addressed. We therefore recommend that social scientists participate in the scenario-construction exercise proposed in Section IV. This will provide an opportunity to begin to trace out the network of relationships and feedback loops between physical, biological, and social and economic systems. Analysis of these complex relationships will help us identify the sensitivities of the various systems and the variables that will be the most useful in an integrated systems analysis. We further recommend a series of research-design workshops to identify in detail the research options described later in this section and to determine actual research sites and costs.

PRIORITY RESEARCH:

o Research Design Workshops. These workshops would be the critical mechanism for launching actual research projects. A series of seven workshops should bring together those actively engaged in the research and consultants with relevant expertise. Each workshop would correspond to one or more of the areas proposed later in this section.

Workshop 1: Climate-Society Data Bank and Historical Studies. Persons working on the development of a climate-society data bank should be brought together with those who will undertake historical studies of past climate-impacted societies, as well as with climatologists, and biological scientists working on responses to climatic variability and climate change.

Workshop 2: On-Site Studies of Current Situations. Participants should be those who are currently involved in on-site studies of stress situations that can be treated as climate surrogates: e.g., farming areas where the consequences of long-term soil erosion and a decline in soil fertility due to the depletion of organic matter seriously affect productivity, agricultural areas affected by strip mining, and particularly the ecologically fragile Southwest. (Some short-term events such as the eruptions at Mt. St. Helens, the Three Mile Island nuclear accident, the exposure to toxic residue of Love Canal, or the 1980 heat wave in the midwest might also warrant study, though CO2 climate change will most likely be an incremental process rather than an identifiable event.) The purpose of the workshop should be to develop common research frameworks for investigation of family, community, governmental, and nongovernmental response behaviors in two types of time frames: 1) "quick response" studies involving perhaps a week at the stressed site; and 2) more in-depth studies of stress situations, lasting from three to four months, with the possibility of longer-term follow-up research, including longitudinal studies, at promising sites. (Longitudinal studies involve follow-up of particular individuals, families, and community institutions over a period of years to identify how they develop and adapt over the longer term.) The workshop should also discuss how to develop the organizational mechanisms for doing quick-response studies and the recruiting of the most promising scholars in the field.

Workshop 3: Responses at the Household and Community Level. Regarding the mechanisms whereby neighborhoods and communities respond to stress and change, participants should discuss how to combine existing research traditions with experimental approaches so as to develop the most productive methodologies for the study of adaptation to climate.

Workshop 4: Governmental Response, Information Processes, and Decision Making. Political scientists, political sociologists, communication specialists, and perception psychologists would be brought together to try to identify the most promising techniques for understanding the complex interactions between government, the scientific community, and the public in the perception of and adaptation to climate changes.

Workshop 5: The International System. ("The international system" includes the UN and its agencies, regional and bilateral relations between national states, international trade, educational and cultural contacts, as well as individual contacts of all kinds.) Social scientists studying the international system, both its governmental and nongovernmental aspects, would be brought together to assess the existing capabilities of international institutions to respond to climate change and the potential of new mechanisms that may emerge.

Workshop 6: Model Linkages for Climate-Impact Studies. Social scientists with experience in systems modelling would explore ways to link the different social-system models developed in the five previous workshops. They should attempt to integrate different social-system models with physical and biological systems subject to climatic changes.

Workshop 7: Health Effects. Social scientists with specialization in various health fields would work with climatologists, entomologists, epidemiologists, geographers, parasitologists and others to plan the development of a disease ecology data bank linked to a data bank on adaptive and maladaptive behavior related to disease patterns.

[The seven workshops should not necessarily delay the start of any specific research projects that might develop from the following proposals. On the contrary, the workshops could provide constructive criticism and feedback to projects that are ready to be undertaken, or are already in process. Each workshop should be sited to minimize travel cost for participants and should last about three days. There should be between 10 and 20 participants per workshop, with some overlap in participation from one workshop to the next to enhance communication and coordination.]

Data Collection

A major need is the collection and analysis of data dealing with climatic variations and related social conditions. A variety of records and studies of stress situations in the past and present must be sifted, and the data then put into forms accessible to other researchers conducting a wide variety of projects in different disciplines. Although some new case-study material may have to be gathered, this task primarily will consist of creating and assembling inventories of existing material relevant to the study of climate stress and its impacts. (See papers by Thedore K. Rabb, and by Richard A. Warrick and William E. Riebsame, Volume II.)

PRIORITY RESEARCH:

o Climate-Society Historical Data Bank. A major cooperative and multidisciplinary effort, linking historians with scientists from various disciplines, should produce a data bank of time series on climatic history. This data bank should span the 13th century to the present and incorporate state-of-the-art climatic information from contemporary records of temperature, precipitation, length of snow cover, windiness, and the incidence of extreme conditions such as frost, hail, floods, and drought. The main focus of the data-collection effort should be on climate, society, and climatic impacts in Europe and North America, with the data separated according to regions and social structures. Data should be assembled as much as possible in time series and in a form that is suitably organized and synthesized to aid analysis. The effort should be organized by an international, interdisciplinary team. The project would require a director, a 20-person interdisciplinary board of scholarly advisors, contributors at related centers, and a research team of two full-time assistants. The basic data bank could be assembled in a period of five to seven years and must be kept current thereafter.

Biological scientists have identified a similar need for a bioclimatic data base. (Much of the social response to climate change will come about through changes in prodution of food and fiber -- and possibly through changes in sea level.) There would be considerable merit in simultaneous and parallel development of both data sets, with a view to exchange of information, multi-disciplinary work, and an eventual integration of results, so that networks of interactions -- between changes in the physical climate, the response of crops and other parts of the biosphere, and adaptation by social units -- can be viewed comprehensively, as it eventually must be.

o Organizing Case Studies. An opportunity exists for creating a network of case studies on climatic impacts. This would include the following activities: 1) stock-taking of conceptual and methodological approaches to climate-impact assessment; 2) establishment of a coordinating body or clearinghouse to keep researchers informed of other case-study activities and findings; and 3) a series of workshops in which researchers with common case-study interests could exchange data, ideas, and results, as well as sharpen common research questions. Also, there is need for a systematic inventory of potential case studies. It would be advisable to initiate the inventory on the basis of objective identification of climatic events, in terms of both long-term change and short-term perturbations. A continuous, coordinated effort involving historians, climatologists, and biological and agricultural scientists could overcome methodological problems. A secondary inventory could involve identification of situations analogous to climatic variation (for example, the migration of settlers to an unfamiliar climatic region). As potential case studies, these analogies could serve as climate-change surrogates in particular time and space contexts for which we do not have climatic events on record.

Impacts on Society of Past Climate Changes

Global and regional climate changes will affect different societies -- and different segments within societies -- in a wide variety of ways. One way to determine the range of impacts is to undertake case studies on how families, political institutions, and sectors such as agriculture have been affected by changing climates in the past. Another promising method is to explore the linkage of climate and socioeconomic models. Possible social effects emerging from a CO_2-induced climate change can be traced out for later inclusion in scenario exercises. (See papers by Theodore K. Rabb, and Richard A. Warrick and William Riebsame, Volume II.)

PRIORITY RESEARCH:

o Case Studies of Effects of Climate Change on Society. Using information collected for the climate-society data bank and from other sources, case studies should be prepared about the effects of climate changes on different societies. Possible topics: agriculture; patterns of settlement and geographic change; political institutions, economic development, and social relations; and people's attitudes and images about the future. Of particular importance for understanding the adaptation of industrial societies will be the study of their climatically most vulnerable areas. Two such areas are Iceland and the Great Plains of the United States. Separate research teams composed of a director, a research assistant, and a board of scholarly advisors should be assigned to each major topic. Each team should work closely with the researchers compiling the climate-society data bank. The effort should take approximately five years.

o Socioeconomic Process Models and Case Studies. Important research involves the linking of major climate and socioeconomic models. Such models are not now interconnected in a manner that allows us to estimate the socioeconomic impacts of climatic fluctuation or to explore the effects of alternative policy options. Development of methodologies for doing so represents a major research opportunity. A second research opportunity involves tracing the actual pathways of climatic impact through empirical case studies. This work is needed to build and refine the more theoretical models. In addition, an important research component would be the examination of impact pathways over time. Such historical time-series analyses should be aimed at identifying trends of climatic impact. This project should take about six years to complete.

Current Climate-Stress Surrogate Situations

Many events lead to environmental changes that have some properties of climate-induced stresses, and require major adaptive responses on the part of affected individuals, families, and communities. They can be treated as climate-stress "surrogates." Some examples of possible surrogates are: major seasonal droughts; prolonged very high summer temperatures; rapidly growing boom towns in isolated, fragile environments; large-scale international migrations, triggered by war or political and social upheavals, or associated with famine or natural disasters; environmental changes associated with chemical pollution or radiation; conditions of long-term soil erosion or loss of soil organic matter from excess tillage; and natural disasters with long-term environmental consequences, such as volcanic eruptions.

Teams should enter an area for varying lengths of time to observe how families and community institutions are affected by stress situations such as those described above. The comparison of data from different studies will enable identification of the strengths and weaknesses of different response units, particularly the family unit and local and national governmental units. No priority research areas will be specified here because these will be generated by Workshop 2. It is proposed, however, that the Department of Energy and the National Science Foundation jointly fund a Quick Response Program for on-site study of climate-stress surrogate events. This should utilize the experience already developed by William Anderson at NSF (NSF Important Notice Number 82, "Special research opportunities associated with the Mt. St. Helens eruption") with the Mt. St. Helens "quick response" program and by other organizations that have sent quick response teams to observe natural disasters. The summer heat wave of 1980 in the midwest is a good example of a situation suitable for on-site investigations. The physical or biological phenomena associated with disasters have received the most study; the behavior of social units as they respond or adapt to the phenomena has been a secondary concern. The focus for this program should be on social behavior.

Societal Response Mechanisms

Societies faced with climate changes in the past have been forced to adjust -- or perish. These adjustments, or adaptations, have taken a variety of forms, ranging from migration to the development of innovative new technologies or social structures. How societies have responded to climate changes should be the subject of intense scrutiny. Were the responses consciously promulgated, or ad hoc? What role did political institutions play? Was the development of new technologies encouraged to deal with climate change, or did such development evolve and get picked up as an adaptive mechanism? Did people voluntarily change their way of living and accept new innovations? These and many other response mechanisms will have a direct bearing in the next century if rising CO_2 levels lead to an altered environment.

A significant proportion of social responses to a changing climate would come from nongovernmental sources. In the case of local and regional climate change, the private sector may devise solutions far more flexible and workable for local conditions than could any distant government body. Cooperatives may be formed to increase agricultural production or to share new technologies. An assessment of local capabilities for solving problems using voluntary organizations (including civic, cultural, youth, and service organizations, churches, labor unions, precinct organizations, and special-purpose associations of women, the elderly, and minority groups) would reveal resources not ordinarily thought of in connection with problems of environmental stress. The extent to which market mechanisms can produce solutions to climate-stress problems should be explored in cooperation with the scenario-building exercises. Another topic would be to examine the capabilities of certain industries, such as the insurance industry, to create stress buffers. (See papers by Richard Warrick and William E. Riebsame, and William I. Torry, Volume II.)

PRIORITY RESEARCH

o Social Responses to Climate Change. A team of social scientists should study how human societies have responded to climate change (or surrogates). They should draw on the research of the climate-society data bank and the case studies of effects of climate change on society. The effort should be divided into six major categories with the following questions: 1) How has awareness of change developed, and how has it led to action? 2) How have ad hoc adaptations operated? 3) Have deliberate, planned responses differed significantly in their efficacy from more spontaneous responses? 4) How have localities responded, by location, size, and duration of the stress? 5) How have regional or national authorities responded? 6) What are the ingredients of successful responses? The research team should consist of a director, two assistants, and an advisory board of scholars from all relevant disciplines. The research will take approximately five years.

o Audit of Past Response Strategies. A major research opportunity lies in conducting empirical analyses of past adjustment strategies. The purpose would be to gain understanding of their effectiveness in actual use beyond theoretical or normative evaluations. The focus should be on studies that relate directly to a CO_2-induced climate change, such as drought adjustment in the United States, Canada, and the Australian Plains. Knowledge of the efficacy of adjustive mechanisms is important for the development of strategies for coping with climate change.

o Community Self Help. As disussed in Section II, climate changes may alter the location and modify important features of agricultural regions, forest belts, rangelands, and fisheries. Established ways of using land and exploiting its products may become untenable. New forms of cooperation that involve the social and spatial organization of settlements, the production and marketing of food, the tenure and protection of land, and the delivery of welfare benefits will probably be called for. The study of various forms of "self-help" should be undertaken. In rural areas, cooperatives, resettlement schemes, land-reform, and experiments with industrial and biomass energy sources as alternatives to traditional agricultural production should be investigated. In urban areas, the development of neighborhood-association movements should be examined. A comparative survey of self-help organizations in countries where they have been effective should be conducted by a team which includes sociologists and economists with rural and urban development experience.

o <u>Community Stress Studies</u>. Households and their environments (i.e., the network of households, commercial, civic, and cultural institutions, and administrative agencies) provide a focus for the study of community stress. Field research in the United States and surveys of anthropological research on rural nonindustrial communities would put into comparative perspective the social and ecological properties of climate-change surrogates (e.g., wars, epidemics, droughts, floods, and hurricanes). The following questions should be addressed: How do households perceive and use their own assets in stress situations and what signals do they send out to the community? What are the traditional inter-household sharing devices? How do governments and markets relate to the household adaptive strategies and what political or ideological precepts guide that relationship? Which responses are buffers and which amplify stress? What prompts communities to use technological innovation as a response, compared to those that use migration? Who are the innovating risk-takers in a community and how do others respond to the innovators? If possible, resettlement communities should be examined to understand the special adaptations required by settlement.

o <u>Family Stress Studies</u>. Research would look at the family as a social system under stress, in contrast to the previous research area, which proposes to examine networks of households in interaction. The primary responder to climate stress is the family. Whether we are talking about the nuclear family, the extended family, or alternative household groupings, these are the units that make the day-to-day adaptations to change. Husbands, wives, children, and extended family members all participate in a restructuring of role patterns. The success of this restructuring depends on well-established characteristics of family organization and integration.

Research on family adaptation to stress has a 50-year tradition; research has been done on family-level adaptation to the Depression, to wartime separation and other war-related traumas, and to natural disasters. This research should be drawn upon in designing the field research protocols. In contrast to the quick-response surveys of families experiencing relatively sudden stress, in-depth studies should be undertaken of families facing long-term environmental stress. The adaptive behavior of farm families in areas of soil erosion, the depletion of soil organic matter and resultant loss of fertility, and recurring drought should be examined from a family perspective. The family restructures its practices to cope with the pressures of an environmental crisis. Family adaptation in climate-change surrogate situations, such as boom towns and possibly chemically damaged environments, should also be investigated. The project would take three years to complete and would require one full-time coordinator, three directors of field research, and six research assistants.

Governmental Response Mechanisms

Given the policy overload that already exists in much of the federal bureaucracy -- the surfeit of problems demanding attention, and limitations on the time and attention of key government officials -- it is essential to examine alternatives to policies that impose further burdens on the government. Regulatory measures may be necessary to cope with aspects of CO_2 effects that cause conflicts, but some combination of market incentives and regulatory requirements may be more effective in achieving adjustment goals. In any case, the proper balance between government intervention and nongovernmental mechanisms is an important area of institutional design and the current research effort would benefit from careful exploration of alternative mixtures.

A CO_2-induced climate change will more likely be a process of changing environmental conditions, rather than an emergency. Nonetheless, a major role of governments is to respond to emergencies, including droughts, floods, and hurricanes, and to prevent looting and assist in reconstruction in the event of these and other natural disasters. Exactly how governments in different societies have responded to emergencies would also be a fruitful research area, as it would reveal the institutions and mechanisms available for coping with social stress, whether it be a rapid event or a slowly evolving climatic condition (which could also be accompanied by weather extremes).

Many strategies for responding to CO_2-induced climate change could also increase our ability to deal with other social problems. Demonstrating linkages between climate change and other problems will increase the likelihood that promising adaptive strategies will be implemented. It is entirely possible that we can make progress toward desirable social goals at the same time we are increasing our ability to cope with climate change. (See papers by Dean Mann, Edith Brown Weiss, and William I. Torry, Volume II.)

PRIORITY RESEARCH:

o Linkages with Other Policy Problems. Research establishing linkages among CO2 strategies, other resource problems, and national aims could facilitate adoption and more explicitly meet the priorities of national goals. For example, how might strategies for coping with climate change, reduction of agricultural drought hazard, and economic-development aims be integrated and implemented in the tier of sub-Saharan developing countries? The CO2 issue probably will be perceived in many parts of the world as a problem for the far-off future. The chances of responses that benefit the entire global community facing climate change would be enhanced considerably by linking CO2 to other, better-recognized problems. Researchers representing various disciplines should investigate possible linkages between the CO2 issue and other social problems.

o Encouragement of Technological Innovation for Pollution Control. Research should consider public policies in different nations which encourage technological innovation to deal with specific pollution problems. This may lead to suggestions on how to encourage the development of technologies to control CO2 emissions. Innovation at the national level is frequently encouraged by direct incentives (e.g., the computer and nuclear power programs in France) or by regulation (e.g., the regulatory policies involving auto mileage and emissions in the U.S.). This research would take approximately two years and should be conducted by a researcher familiar with international law and regulation.

o Research on "Castastrophes." Emergency operations are vital for preventing and mitigating crises of scarcity -- such as those instigated by stresses of climate -- and involve the distribution of supplies and services to victims. Research in this area should be related to the quick response studies suggested earlier, but with more emphasis on longer-range, total systems research. Research on emergency operations in the United States and in other societies should recognize that the possible effects of a CO2-induced climate change may involve slow, barely perceptible changes in the mean, as well as weather "events" -- such as heat waves or droughts. Research should be conducted by a team of social anthropologists, geographers, social psychologists, and political scientists and should include a series of relevant case studies.

International System

Climate models indicate that different regions will be affected in different ways by a CO_2-induced climate change. Some regions may benefit from such a change. The Soviet Union, for example, may experience longer growing seasons in its northern regions; Bangladesh and India may benefit from more regular monsoons; rice production in China may increase. On the other hand, some nations may suffer because of changing climate conditions. The international aspects of the CO_2 question are thus extremely complex. Will nations voluntarily abate CO_2 emissions? Can international agreements be devised to accommodate migration and other adjustments? Will the balance of economic and political power shift under new climatic regimes? What kinds of conflict-resolution mechanisms and skills will be needed to avoid resort to armed conflict by aggrieved nations? Will general circulation models or other sources of climate information be refined enough to predict reliably how different regions will be affected by climate change? These and other issues merit serious consideration by social scientists. The answers are likely to alter the directions of physical science research as well. (See paper by Edith Brown Weiss, Volume II.)

PRIORITY RESEARCH:

- Impacts of Differential Distribution of Climate Resources on the Global System. What are the probable global-spatial distributions of climate impacts under given climate scenarios? Will climate-related perturbations such as droughts and tropical cyclones act to further increase or decrease the discrepancies between rich and poor nations, given the present global economic system? CO_2-induced climate change may alter the frequencies of such events in the future, but information on the events themselves, the nature of their impacts, and the implications for global equity is available now. In light of the difficulties physical scientists will continue to have in specifying details of future climate changes, and the difficulties social scientists will have in predicting accompanying social changes, an alternative is to assess past global trends in climate impacts in order to ascertain the possible directions or magnitudes of impact. Historical case studies of past climate-related changes in key food-producing areas of the world could provide valuable clues to future developments in world provisioning. This may also throw light on the international repercussions of future climate perturbations in food production and distribution, and the areas where the potential for famine and catastrophe is now building.

o Regulation of Trans-Boundary Pollution. One way to study international aspects of the CO_2 issue is to regard CO_2 as a substance, the emission of which by one country could potentially harm another. The situation then becomes somewhat similar to transboundary pollution cases, such as the Trail Smelter Arbitration between the United States and Canada and other current national and regional air and water pollution problems. In this context, we should examine U.S. experience with an ambient air quality standard and pollutant-specific emission standards to control air pollution and European efforts to control water pollution on the Rhine. The acid rain problem in Europe and between Canada and the United States raises similar issues. What new international mechanisms will be needed to deal with these problems, and what are the processes by which these mechanisms may be developed?

o Changing International Balance of Economic and Political Power. A warming trend can be viewed as a long-term process which may affect comparative economic advantage. There are many elaborate codes on trade practice which have been set up to cope with consequences of shifts in comparative advantage among developed countries. These codes are concerned with subsidies and countervailing duties. There are also domestic arrangements -- dislocation allowances, among others -- to cope with the human consequences of obsolescence. Climatic warming can also be regarded as a long-term trend affecting the balance of political power between countries. One example of substantial shifts in political power following economic change is found in the greater influence of OPEC countries on the international system after 1973. Studies of comparable past shifts in the international balance of power, and of the processes involved, should be undertaken to develop scenarios of a peaceful adaptation to change in the balance of power. The project design and budget should be developed in Workshop 5. (See also Conflict and Mediation Processes, listed in the next research area.)

Risk Perception, Information, and Decision Making

A pivotal aspect of the CO_2 question involves how people in different cultures perceive scientific and other information and make decisions regarding adaptation or other responses to climate change. This involves not only lay people, but also the many kinds of experts who provide information on climate changes or societal responses and the policymakers at all levels of society who decide how to act on that information. This aspect of the CO_2-climate issue raises many provocative and reseaichable questions in the field of social psychology. How appropriate are the judgments of experts and decision makers? Where do personal biases creep into expert judgments? What kind of information does the public need to comprehend the knowns and unknowns of the CO_2-climate issue? How will families perceive the issue and make decisions regarding their way of life? These and other concerns merit research so that outcomes and options related to CO_2 issues can be better explained by experts -- and comprehended by decision makers and the general public. (See paper by Baruch Fischhoff and Lita Furby, and Edith Brown Weiss, Volume II.)

PRIORITY RESEARCH:

o Perceptions by Nontechnical Persons of CO_2: Presentation of Information. An important and complex project involves understanding and improving nontechnical policymakers' perceptions of the facts of CO_2-induced climate change or its impacts. Among the primary research questions for such a study are: How do lay policymakers interpret the information presented to them by experts? Is this testimony about climate consistent with their direct sensory experience of weather and its impacts? If not, how are the conflicts resolved? What kinds of information cause the greatest difficulties for public understanding? How can such problems be remedied, so that authorities can make the best use of their own experience? A study examining these issues should produce the following products: scientific papers extending existing judgment work to perception of long-range climate change and opening new research areas; surveys of public knowledge and opinion on CO_2-induced climate change and its potential impact; and guides for experts on presenting climate information, and bulletins to experts on what the public wants to know. Participating disciplines should include psychology, sociology, and anthropology, plus some technical consultation with climatologists and survey researchers. The initial stage of the climate research program should place heavy emphasis on this research area so as to establish the groundwork for effective dissemination of later products of the program. This research would require four to five person-years per year over five years, and should be followed by an appraisal of progress and needs. Additional resources would be needed if representative surveys or broad educational programs are conducted.

o Judgment and Role of Experts. Where do subjective judgments enter into scientific analyses? How explicit are those judgments? How well do experts identify and assess such judgments? Can we make better use of experts by having a better appreciation of the limits of their abilities? These and similar questions have direct bearing on the CO2 issue. Technical papers should be commissioned reporting the results of research on the nature and quality of expert judgment in assessing the facts about CO2-related issues. Guides should be written translating the conclusions of these technical reports into a form useful for policymakers outside the expert community (i.e., government, the nontechnical public, intervenors, social critics). Finally, research can help develop practical procedures for better exploiting the educated intuitions of experts. Participating disciplines in such an effort should include psychology, statistics, and cognitive science. A serious commitment to this research area would require an investment of 3-4 person-years of a principal investigator over a 10-year period during which applications would assume an increasing role and methodology and data analysis would diminish. Workshop 4 should suggest a project design and budget.

o Understanding How Alternative Responses to Climate Change Are Evaluated. Even if creative responses to the CO2 issue are devised, it is not clear that these can be implemented. Much depends on how the public evaluates various options put before it. This raises complicated questions: How do people combine multiple and conflicting risks and benefits of various options into a single decision? How can opinions on these issues be accurately elicited so as to inform government officials? Finally, how can faulty elicitation methods (asking the wrong questions, or asking them the wrong way) distort the values expressed through them? An examination of these issues should produce methods for surveying attitudes toward the consequences of climate change and options for dealing with them. Also, there should be analyses interpreting what the public wants, what it might want if better informed, and what the consequences would be of adopting policies consistent with those desires. Participating disciplines should include psychology, sociology, philosophy, anthropology, and economics. Workshop 4 should develop the project design and budget.

o Conflict and Mediation Processes Relating to Climate Change. Climate change could pit nation against nation and group against group, because as some regions "win" and others "lose," conflicts and dilemmas are likely to be created, or existing ones will be exacerbated. What kinds of mistrust and misunderstanding might emerge, and how might they be avoided? Can frameworks or options be devised for conflict resolution? Research dealing with these issues should attempt to produce new ways of studying resource distribution decisions; studies of actual distributional judgments and behavior; and a comprehensive delineation of the ways these issues are addressed in different cultures and different historical periods. Participating disciplines should include psychology, political science, sociology, economics, philosophy, and history.

o Climate Research Feedback to Policymaking Bodies. Research is needed on how the results of climatology can be made continuously available to relevant policymaking bodies at national and international levels. Similarly, climatologists and those involved with climate impacts studies need to be continuously informed regarding the kinds of information needed by governmental authorities and policymakers and the most helpful ways of presenting this information, taking account of the inherent uncertainties of the sciences involved. Case studies should be researched, for example, regarding the impact of advances in stratospheric chemistry on the use of aerosols.

Effects on Human Health

Increased atmospheric CO_2 levels and the resultant climate change will profoundly influence conditions of health and disease. Impacts will be felt in nutrition, insect-transmitted and other transmissible diseases, water for sanitation and hygiene, migration and stress, and health-related technological effects (for example, increased use of pesticides) of trying to counter biological changes. The severity and extent of all such impacts will depend upon the nature of the climate change.

The National Ocean and Atmospheric Administration has estimated that the exceptionally hot summer of 1980 in the central and southern United States resulted in at least 2000 deaths that otherwise would not have occurred. A rise in average temperature in this region of several degrees centigrade is projected from climate models for a doubling of atmospheric carbon dioxide. This could result in summer temperatures during exceptional years much higher than those experienced in 1980. Correspondingly, the effects on human mortality and morbidity might be much more severe.

Climate change triggered by increased CO_2 could cause floods and droughts leading to malnutrition and famine which would in turn clearly impact upon human health. If climatic warming causes disintegration of the West Antarctic ice sheet and a consequent rise in sea levels, the richest and most densely populated agricultural lands, including the deltas and much of the valleys of the great rivers -- Nile, Brahmaputra, Mekong, Yangtze, Hwang Ho, Mississippi, etc. -- would be flooded, as well as extensive coastal plains. CO_2-induced climate change could conceivably force hundreds of millions of people to migrate, or else perish. The health effects could be enormous. Migration itself has been shown to cause stress. Migration also places tremendous demands upon the infrastructure of housing, transportation, sanitation, and food distribution. The collapse of such infrastructures after a catastrophe has different effects in more and less industrialized countries, but would result in serious public health hazards wherever collapse ocurred. Forced migration also disrupts cultural patterns of adaptation and protective behavior developed over generations to cope with the stresses and health hazards associated with a given environment. The cultural factors of disease causation as triggered by climate change and migration are especially unpredictable.

One of the most serious impacts of climate change upon health would result from changes in the patterns of transmissible disease. The environmental factors that are critical to the distribution of particular insect or animal vectors are those most likely to be affected by climate change: precipitation and groundwater, wind patterns, and seasonal temperature extremes and durations. A CO_2-induced climate change would alter these variables and could be multiplied, in effect, because of the ecological interdependence of all living things.

Increasing aridity could prompt more use of irrigation (which in the dry tropics has been synonymous with the extension of schistosomiasis), and with changes in water quality and quantity which could affect transmission of diseases both directly and indirectly. On the other hand, warmer and wetter conditions would generally favor a wide variety of fungal, nematode, bacterial, and viral agricultural pests as well as disease vectors.

The increase of carbon dioxide in ambient air at the levels predicted is not known to cause effects on human health. Research to date has concentrated on CO_2 levels which exceed many times those predicted in the usual climate change scenarios. We recommend, however, long-range studies of continuous exposure over the lifetimes of several species of test animals to CO_2 levels in the range of 500-1000 ppm. Additionally, climatic warming in temperate zones could bring an increase in temperature inversions which cause buildup of atmospheric pollutants and resultant health effects. (See paper by Melinda Meade, Volume II.)

PRIORITY RESEARCH

o Bioclimatic Health Data. There should be an inventory and collation of existing health-related bioclimatic data. The data should be referenced geographically. There is considerable knowledge of the life cycle needs and habitat conditions of most medically important insects and host animals, but these have not been tied to the geographical distribution of such conditions. Existing data sources and information systems need to be brought together on the same scale and basis and directed toward illuminating the interrelations of climatic, disease, and cultural patterns.

o Crop and Livestock Distribution. There should be an effort to assemble and refine the data on crop and livestock distributions relative to ecological (principally meteorologic) parameters in order to identify marginal areas where changes could be detected first and where the impacts on human health can be expected to be most severe. This information should be used to model the ranges of adaptive strategies.

o Workshops on Human-Health Effects. A series of workshops should:

a) Collate and map existing knowledge on disease ecology. This workshop would include an interdisciplinary group of medical sociologists, anthropologists, climatologists, entomologists, epidemiologists, geographers, parasitologists, and others, for the organization of a baseline data bank. By incorporating the needs suggested by other panels, and by incorporating other data (agro-climatic, historic-climatic) the establishment of such a baseline data bank could be the most important project immediately attainable.

b) Identify adaptive and maladaptive cultural behavior related to disease patterns. Much is known in an uncoordinated way about the cultural ecology of various diseases, but this needs to be brought together and cross-calibrated with other climatic, agricultural and social information as it becomes available.

c) Construct scenarios of future migration patterns. Climate change could profoundly affect regional carrying capacities and result in large-scale population redistribution. We need to examine the possible regional distribution of climate change, its effect on agriculture and human settlements, and past patterns of migratory response to stress and hazards, and project as well as possible the impacts on human health of anticipated migration caused by climate change.

d) Compile data on mortality and morbidity occurring during exceptionally hot summers under present climatic regimes, particularly in rural areas and city slums where many people do not have shelters that give protection against extreme heat. Interannual variation could result in occasionally hotter summers than ever experienced before in regions at mid-latitudes, if average temperatures in these regions rise by several degrees centigrade. Extrapolation to these more extreme future conditions may be possible if sufficient data on recent hot summers of different intensity can be collected and analysed.

IV
ECONOMIC AND GEOPOLITICAL CONSEQUENCES

Economics plays an important role in determining CO_2 emissions and the implications for human activities worldwide, though it has no role in predicting the physical changes affecting the atmosphere and oceans that might result from a CO_2-induced climate change. Economics can also clarify policy choices open to society regarding prevention of a buildup of CO_2 or adaptation to CO_2-induced climate change.

The methods of economics applied to a wide array of CO_2-triggered phenomena will make a more important contribution than investigations of the economic phenomena themselves. Perhaps the most useful economic tool is scenario construction and analysis. Scenarios developed by teams of physical, biological, and social scientists can create a framework for viewing the complex implications of the global CO_2-climate situation.

Scenario Analysis

In some sciences, such as physics, fundamental laws are presumed to be known and to apply universally. But their application to real-world events requires that assumptions be made about what physical effects are so small as to be negligible or untreatable in detail. Which effects are second order or must be treated statistically (i.e., parameterization) depends on the circumstances. For example, effects such as superconductivity are negligible at standard temperature and pressure, but dominate at absolute zero. In other areas of scientific inquiry, however, particularly the social sciences, there are few generalizations that hold for a wide range of conditions. Answers to inquiries depend on the specific situation in question.

The physical, biological, and social sciences will be involved in answering important questions about possible CO_2-induced climate effects and scientists from each of these areas should participate in defining the situations of interest. While fundamental, isolated investigations of fluid dynamics and of social psychology, for example, would eventually strengthen those disciplines and thus promote better understanding of many aspects of the CO_2 issue, progress would be very slow. Much time can be saved by targeting and integrating the research. Since there are important feedbacks among atmospheric and ocean dynamics, marine and land biota, and agriculture and energy use, the CO_2 situation can best be defined via an integrated picture -- that is, a scenario.

A scenario has three major components: 1) a set of initial conditions; 2) cause-and-effect models which relate these initial conditions and perturbing forces (such as specific climate changes) to outcomes; and 3) analyses of the implications of these outcomes. A CO_2 scenario would encompass a range of variables which characterize the state of the atmosphere, oceans, biota, and human activities. Such scenarios can and should provide the intellectual organization for a research program on CO_2-climate impacts. The scenario provides a framework for integration and coordination of disparate studies -- ranging, for example, from the physiological effects of rising CO_2 levels on phytoplankton to the economic impacts of climate change at the farm level. Such a framework focuses attention on the entire CO_2 picture. Viewing the problem as a whole helps determine whether pieces of the overall picture are missing, the kinds of information a project must produce in order for its research results to be useful to other studies, the timing of research outputs to ensure that results will be available when needed, and feedback loops among the parts that reveal what information is required from other parts and how changes in one element affect other elements. Formal scenario analyses have already been used to study a number of complicated social issues, including energy policy, and much has been learned about the method and its possible contributions.

The complexity of CO_2-effects research should not be underestimated. There are many aspects and many interactions. Without a coherent framework, each investigator will pursue idiosyncratic questions using idiosyncratic assumptions. Since decisions regarding policy toward CO_2 require integration of those diverse contributions, a coherent framework is needed, and scenario analysis is the suggested tool.

PRIORITY RESEARCH:

o <u>Defining Integrated CO_2 Scenarios</u>. This research area is of the highest priority. Its objective should be to produce a set of up to six integrated scenarios defining interesting and plausible combinations of assumptions about climate, ocean dynamics, marine biota, land biota, and agriculture, and their social implications. The scenario building would eventually be conducted in an exercise bringing together scientists with backgrounds in climatology, oceanography, marine biology, land biology, agronomy, economics, sociology and anthropology, social psychology, and political science.

The exercise would begin with perhaps two assumed time paths of CO_2 emissions. The climatologist and oceanographer on the team would trace out two sets of atmospheric and oceanographic outcomes for each of the

CO_2 paths. With these in hand, the two biologists would attempt to trace out changes in the biosphere, sketching more than one outcome where needed. The agronomist would attempt to see how the current level and mix of food and fiber would be produced in the new regime via changed cropping patterns, new crop strains, and increased irrigation, for example. Finally, the social scientists would attempt to trace out the implications of these physical and biological changes for human activity and welfare. Total energy use, fossil fuel use, geographical location, and economic and residential activities are among the implications which should be given attention. These results would be fed back to the initial assumptions about CO_2 emissions and, if not consistent, would begin a new round in order to find a consistent scenario.

Each participant would presumably have a set of causal models, or at least some generalizations, from which to draw judgments about the implications of each assumption. As the general conditions became better defined, each participant could attempt to particularize these models to the current situation or to define the research required to do so. The scenarios would require each participant to specify the types of inputs required for his task and the types of outputs he could provide. Aspects of the problem which could not be modelled by these participants would be specified. Each participant would attempt to specify the range of uncertainty associated with his outputs and the factors that would lower uncertainty. The anticipated result of such an exercise would be a set of consistent scenarios with uncertainty bands about each.

One reason why this project would require a month of full-time work by a team is that the participants would have to learn a common language and gain an understanding of the other disciplines and their contributions to the problem. The substantive work of actually putting together the scenarios would probably take no more than a week. Participants would be responsible for writing reports on the additional research required in each area as a result of the exercise. Participants would retire to their home bases and work to flesh out the scenarios via the causal models or substantive knowledge in each discipline, and to work on some of the additional research identified by the initial exercise. Some months later, the group would reconvene for a week to discuss the contributions of each participant, to modify the scenarios, and to discuss uncertainties and the research projects flowing from the scenarios. If a research project produced results similar to those assumed by the scenario writers, this would bolster confidence in the scenarios. Insofar as assumptions are contradicted by new research, new implications would have to be traced out in the scenarios. A large number of scenarios could be identified, too many for serious consideration.

Since a primary objective of social planning is guarding against disaster, the emphasis should be on unfortunate or pessimistic scenarios, although at least one optimistic scenario should be fleshed out. One scenario should embody the most pessimistic of the set of reasonable assumptions about climate, the oceans, and other physical and biological phenomena. Social or policy responses would be assumed to be forthcoming with suitable lags. Under such conditions, what are the potentials for disaster? What actions now, such as the development of technologies, networks for measuring the crucial physical changes, or adjustments in society's capital stock, would lower social cost in such a situation? The optimistic and pessimistic scenarios are likely to provide the most insightful cases, exposing crucial aspects of social and economic structure and events to be watched.

[There is merit in comparing two or more independently-developed scenario analyses. The comparison of separate ideas and estimates emphasizes the value of scenarios as a method of illustrating and considering the implication of uncertain futures.]

Economic Aspects of Scenarios

Scenarios will produce projections of the effects of climate change on agricultural yield, energy required for space conditioning, and changes in consumption patterns. Some of these scenario outputs must come from economic models, such as those that calculate the demand for air conditioners as a function of climate, price, and income, or models dealing with demand for energy generally, given changing climate. Such models can be drawn from a substantial literature.

Once scenarios are completed, a necessary task will be the aggregation of outputs into measures to evaluate the social desirability of a scenario. Prices, wages, and measures of economic activity are a widely used approach for evaluating one set of outputs. Some economists insist on developing dollar measures for all outputs so that a dollar-benefit number can serve as an evaluator of each scenario. Where this can be done, it simplifies decision. However, there are conceptual difficulties in, for example, deriving a dollar value for the preservation of a cultivar that would otherwise have become extinct. In many cases, it is more fruitful to stop short of complete aggregation into a single value and simply to list some outcomes. While conceptual problems lurk behind each new valuation task, the provision of economic models for adjustment and for valuation are straightforward. Their application is painstaking and must be carefully reviewed, but there probably are no major research needs at the present time.

Social Aspects of Scenarios

A scenario is conceptually incomplete until its important implications are traced out. For example, we have learned little if we know merely that climate will change. By knowing the implied changes in economic activity, many of the important implications have been specified. But we also need to know the implications for individual behavior and social institutions. A large change in climate, with resulting changes in biota and in agriculture and other economic activities, might cause important changes in ways of life, social institutions, and individual behaviors. The result could be, in some cases, increased tension between various groups, possibly resulting in violence. If possible, we should learn which groups will gain and which will lose.

Scenario analysis provides a fruitful way in which social scientists can interact with atmospheric physicists, oceanographers, biologists, and agronomists. The task and importance of each discipline is obvious within this context. Scientists can communicate what each needs to know and the uncertainties surrounding what each can say. Each can participate in the design of scenarios and ensure that questions are posed in a felicitous manner.

As stated earlier, social scientists should have an integral role in designing and filling in the details of the scenarios. They should attempt to develop a common language with physical and biological scientists in order to understand the potential contributions of each discipline.

The CO2 scenarios will identify social issues common to many analyses of CO2-climate impacts that will require research in depth. When such an issue is discovered, it should become the subject of a specific research project. Care must be taken so that the problem definition, units of analysis, and results all feed back into the scenarios. It is currently impossible to predict what these research issues will be, or the personnel, budgets, and timing needed.

International Issues

The CO_2 issue is inherently international. Unfortunately, it is not inevitable that conflicts among nations will be settled by legal means. Some nations will benefit from climate change while others will lose. Some will resist abating CO_2 emissions and some will resist adaptation strategies. Short of threatening war, there is no current way of compelling a nation to do something it perceives to be not in its interest.

A fruitful area of research postulates that individuals act in their perceived self-interest, and scientists then explore the resulting behavior of individuals and institutions. For example, individuals will band together to protect themselves against violence and to enforce contracts. Such a framework seems ideal for investigating interactions among nations.

PRIORITY RESEARCH:

- <u>Modelling International Responses to CO_2-Induced Climate Changes</u>. Research that builds on perceived self-interest should determine what international institutions are in the self-interest of nations in the light of climate changes. Specific research questions might include: What institutions could eliminate externalities and promise gains to all who join? What institutions would be required for the monitoring and enforcement of agreements? What side payments would be required? Would some nations be coerced to join? This research area is a purely theoretical examination of the implications of national self-interest with regard to the CO_2 question, and of the international institutions that should emerge because of this issue. This research should result in models predicting future international behavior (in an idealized world).

- <u>A Survey of Current International Institutions</u>. A second research area should assess current international institutions in light of the theoretical models developed in the previous proposal. Specific research questions might include: How do current international institutions correspond to the idealized models? Which institutions could be modified most easily to fit the models? How could the ideal institutions be implemented? What can be learned from international history to refine the model?

Modelling Issues

A number of research areas dealing with various modelling issues are important and feasible, and should be investigated as soon as possible. Research results from these initiatives will contribute greatly to the construction of integrated CO_2 scenarios.

PRIORITY RESEARCH:

o Economic Models of Resource Depletion. An important research issue involves economic models of the depletion of natural resources, focusing on the role of CO_2. Existing natural resource models should be surveyed and then adjusted to the unique characteristics of CO_2. Some models will require computer simulation. This research would require approximately one year. The budget should provide for a principal investigator for six months, computer time, travel funds and research assistance. Results should suggest theoretically optimal emissions patterns for CO_2, and the social costs of restraining emissions.

o Further Development of the Nordhaus Model. One particular natural-resource model (see paper by William D. Nordhaus, Volume II) has been tailored to CO_2 and represents a preliminary working through of the issues. The Nordhaus model makes a notable contribution and is worthy of further exploration and expansion. Researchers should explore the implications of a wide range of assumptions within the Nordhaus model and modify the model to encompass other specifications of the various equations. This effort would last approximately one year, and should have a budget to provide for a principal investigator, adequate computer time, a research assistant, and travel funds. This effort should explore a range of assumptions and produce information about the outcomes of various assumptions and policies.

o Decision Analysis of CO_2-Induced Climate Changes. Researchers should explore the implications of policies currently available to authorities and policymakers regarding emissions of CO_2 and adaptation to climate change. Researchers should also review alternative frameworks for making decisions in the face of uncertainty and isolate those of most relevance to CO_2. Current CO_2 research is intended to provide information to decision makers by 1985 or shortly thereafter. We should begin now to isolate the questions that must be answered to inform policy, concentrating on the questions of first-order importance. A decision-analysis framework should tell us which issues are most important and which increments in knowledge are crucial to making better decisions by 1985. (This research area thus represents a simultaneous and alternative approach to the scenario-writing exercise proposed earlier.) An investigator should perform a decision analysis of the CO_2 issue and should be prepared to talk with experts in the field, stay abreast of current research, and be able to discuss results of research with the Department of Energy. This effort should produce a list of relevant policy choices and their implications. It should serve to draw together the diverse projects about CO_2 effects in terms of their policy implications, and pose questions to other investigators. The budgetary requirements for this research initiative should be adequate to cover one researcher, computer time, and travel expenses.

o <u>Scenario Method Development</u>. Several aspects of scenario development need further investigation. In particular, a CO_2 scenario will be dominated by uncertainties associated with many of the models and about such crucial factors as the future economic health of the nation and world. Uncertainty must be modelled explicitly in order to recognize how much confidence analysts should place in any scenario outcome. Techniques must be explored as to ways in which uncertainty can be lessened -- by clarifying obscure areas, improving decision procedures, or establishing critical dates for decisions. This research area is a theoretical investigation of scenario methods, focusing on CO_2. Methods that will sharpen the scenario analysis should be produced. Funding should be adequate to cover approximately six man-months spread over one year, computer time, research assistance, and travel.

o <u>Determining Optimal Flexibility and Resiliency</u>. An important research issue involves the theoretical relationship between the amount of resiliency that should be built into capital as a function of the rate of change. Flexibility and resiliency, both in human and physical capital, come at a price. Societies do not desire maximum resiliency, since that is too expensive, but rather optimal resiliency. Given some assumptions about the amount of future change and uncertainty, one can determine optimal flexibility and resiliency of the capital stock as a function of price. However, it is likely that the U.S. capital stock is currently so rigid and inflexible that current output would rise as the capital was made more flexible. This research area should focus on the costs of resiliency, with modelling of social costs as a function of future rates of change and the costs of resiliency. Funding should be adequate to cover six man-months spread over one year, computer time, research assistance, and travel.

o Mitigating Strategies. Exploration is warranted of "mitigating strategies" designed to lower social costs associated with CO2 changes and to lower social costs associated with other shocks. It is likely that little will be done to abate CO2 emissions until there has been a substantial effect on climate. Thus, attention must be given to ways of easing adaptation to the new climate regime. Researchers should investigate what can be done to ease and speed adjustment, investigating the factors that facilitate social and economic change. Funding should be adequate to cover approximately six man-months spread over one year, travel, and research assistance. The output of this research will be identification of conditions that facilitate change, and policies that lead to more rapid and less costly adjustments.

o Agricultural Adaptation. Commercial agriculture is likely to be the industry most sensitive to climate change. An investigation should be done of the aspects of agriculture which are most sensitive and the aspects of climate which are most important. We should then attempt to find historical analogues of each production and climate sensitivity, and investigate the pace and nature of adjustment. For example, hybrid seed, salinization problems on irrigated land, pesticide bans, and the introduction of irrigation represent major challenges to agriculture similar to climate changes. Much can be learned about climate change stress from examining the stresses associated with each of these challenges. This research area should take about six man-months spread over one year. Much of the research will take the form of reviewing previous studies.

o Adaptability of Human Institutions. A general study should be conducted of the factors that influence adaptability of individuals and human institutions to changes in the environment. What factors foster change? What factors impede it? This study should take about six man-months spread over one year. A large literature exists on this question, although it is largely theoretical.

Appendix A
Volume II

Commissioned Papers

I. CRYOSPHERE, OCEANS, AND MARINE BIOTA

Response of the West Antarctic Ice Sheet to CO2-Induced Climatic Warming: A Research Plan -- Charles R. Bentley, University of Wisconsin

Potential Effects on Arctic Sea Ice of a CO2-Induced Global Warming -- Norbert Untersteiner, NOAA

Influence of Short-Term Climatic Fluctuations on Permafrost Terrain -- Jerry Brown, U.S. Army Cold Regions Research and Engineering Laboratory; John T. Andrews, University of Colorado

Potential Effects on Ocean Dynamics of an Inrease in Atmospheric Carbon Dioxide -- Michael McCartney, Woods Hole Oceanographic Institution; Henry Lansford

Effects of Increased CO2 on Ocean Biota -- Osmund Holm-Hansen, University of California, San Diego

II. TERRESTRIAL BIOLOGICAL RESOURCES

Effects of Increased CO2 on Photosynthesis and Agricultural Productivity -- Donald N. Baker, Mississippi State University; L. Hartwell Allen, Jr., University of Florida; Jerry R. Lambert, Clemson University

Direct Effects of Increased Concentrations of Atmospheric Carbon Dioxide on Managed Forests -- Larry W. Tombaugh, Michigan State University; Donald I. Dickmann, Michigan State University; Douglas G. Sprugel, Michigan State University

Impacts of Rising Atmospheric Carbon Dioxide Levels on Agricultural Growing Seasons and Crop Water Use Efficiencies -- James E. Newman, Purdue University

(Terrestrial Biological Resources, continued)

Alleviation of Environmental Stress on Renewable Resource Productivity -- Gordon S. Howell, Michigan State University

Effects on Agricultural Plant Pests -- Dean L. Haynes, Michigan State University

Effects of Climate Change on Animal Agriculture -- H. Allen Tucker, Michigan State University

Response of "Unmanaged" Ecosystems -- Boyd R. Strain, Duke University; Thomas V. Armentano, Institute of Ecology

Ecological Consequences of a CO2-Induced Climatic Change on Forest Ecosystems -- W. Carter Johnson, Virginia Polytechnic Institute and State University; David M. Sharpe, Southern Illinois University

Research Needed to Determine the Present Carbon Balance in Northern Ecosystems and the Potential Effect of Carbon Dioxide Induced Climate Change -- Philip C. Miller, San Diego State University

Effects of CO2-Induced Climate Change on Freshwater Ecosystems -- Charles C. Coutant, Oak Ridge National Laboratory

Research Issues in Grazinglands Under Changing Climate -- Dennis F. Pendleton, Colorado State University; George M. Van Dyne, Colorado State University

The Use of Paleoclimatic Data in Understanding and Possibly Predicting How CO2-Induced Climatic Change May Affect the Natural Biosphere -- Thompson Webb III, Brown University

Climate Change and Agricultural Production in Non-Industrialized Countries -- Lloyd E. Slater, Aspen Institute for Humanistic Studies, Rapporteur

III. SOCIAL AND INSTITUTIONAL RESPONSES

CO_2 and Climate Change: Anthropological Perspectives -- William I. Torry, West Virginia University

Responding to CO_2-Induced Climate Change: Opportunities for Research -- Richard A. Warrick, Clark University; William E. Riebsame, Clark University

Climate and Society in History -- Theodore K. Rabb, Princeton University

Research on Political Institutions and Their Response to the Problem of Increasing CO_2 -- Dean E. Mann, University of California, Santa Barbara

International, Legal and Institutional Implications of an Increase in Carbon Dioxide -- Edith Brown Weiss, Georgetown University

Psychological Dimensions of Climatic Change -- Baruch Fischhoff, Decision Research; Lita Furby, Wright Institute

Interdisciplinary Research and Integration: The CO_2 Problem -- Robert S. Chen, Climate Board, National Academy of Sciences

Effects of Climate Change on Animal Health -- Melinda Meade, University of North Carolina

IV. ECONOMIC AND GEOPOLITICAL CONSEQUENCES

Theoretical and Empirical Aspects of Optimal Control Strategies -- William D. Nordhaus, Yale University and Cowles Foundation

A Conceptual Framework for Research About the Likelihood of a "Greenhouse Effect" -- Mancur Olson, University of Maryland

Adaptive Approaches to the CO2 Problem -- Roger G. Noll, California Institute of Technology

Planning for Climate Change: Scenario Construction and Evaluation -- Dennis Epple, Carnegie-Mellon University; Lester Lave, Brookings Institution

Contributed Paper

The Potential Response of Antarctic Sea Ice to Climatic Change Induced by Atmospheric CO2 Increases -- S.F. Ackley, U.S. Army Cold Regions Research and Engineering Laboratory

Appendix B

CONTRIBUTORS TO COMMISSIONED PAPERS
(Workshop Participants and Experts Consulted)

RESPONSE OF THE WEST ANTARCTIC ICE SHEET TO CO2-INDUCED CLIMATIC WARMING: A RESEARCH PLAN

April 8-10, 1980
Orono, Maine

Charles R. Bentley, University of Wisconsin

Arthur Bloom, Cornell University

Harold Borns, University of Maine, Orono

William F. Budd, University of Melbourne, Australia

James A. Clark, Sandia National Laboratories, Albuquerque

John W. Clough, University of North Carolina

George Denton, University of Maine, Orono

David J. Drewry, Scott Polar Research Institute, England

J. L. Fastook, University of Maine, Orono

Anthony J. Gow, U.S. Army Cold Regions Research and Engineering Laboratory

John T. Hollin, University of Colorado, Boulder

Terry J. Hughes, University of Maine, Orono

Stanley S. Jacobs, Lamont-Doherty Geological Laboratory

Kenneth C. Jezek, University of Wisconsin, Madison

Thomas B. Kellogg, University of Maine, Orono

Wesley LeMasurier, University of Colorado, Denver

Craig S. Lingle, University of Wisconsin, Madison

John H. Mercer, Ohio State University

Hans Oeschger, University of Bern, Switzerland

W.S.B. Paterson, Polar Continental Shelf Project, Canada

Uwe Radok, University of Colorado, Boulder

Charles F. Raymond, University of Washington, Seattle

Dominique Raynaud, Laboratoire de Glaciologie, France

Gordon de Q. Robin, Scott Polar Research Institute, England

W.F. Schmidt, University of Maine, Orono

Charles Swithinbank, British Antarctic Survey, England

Robert H. Thomas, Cambridge, England

Hans Weertman, Northwestern University

Ian Whillans, Institute of Polar Studies, Ohio State University

Francis S.L. Williamson, National Science Foundation

Jay Zwally, Goddard Space Flight Center, NASA

CLIMATE CHANGE AND THE ALLEVIATION OF ENVIRONMENTAL STRESS
IN RENEWABLE RESOURCE PRODUCTIVITY

January 9-11, 1980 - East Lansing, Michigan
March 3-4, 1980 - Kansas City, Missouri

Jon Bartholic, Michigan State University

William Breidenbach, University of California, Davis

David R. Dilley, Michigan State University

Dean R. Evert, Coastal Plains Experiment Station

Kenneth Frey, Iowa State University

Milton George, University of Missouri

Gordon S. Howell, Michigan State University

E.T. Kanemasu, Kansas State University

Bernard Knezek, Michigan State University

C.R. Olien, Michigan State University

Larry Parsons, Department of Fruit Crops

C.J. Weiser, Oregon State University

EFFECTS OF CLIMATE CHANGE ON ANIMAL AGRICULTURE

May 9, 1980 - Boyne Falls, Michigan
June 3-4, 1980 - East Lansing, Michigan

David R. Ames, Kansas State University

Jon F. Bartholic, Michigan State University

G. LeRoy Hahn, U.S. Dept. of Agriculture, Clay Center

W.E. Larsen, U.S. Dept. of Agriculture, St. Paul

Gordon C. Marten, University of Minnesota

Melinda Meade, University of North Carolina, Chapel Hill

James E. Newman, Purdue University

Donald Polin, Michigan State University

Larry R. Rittenhouse, Colorado State University

James Simpson, University of Florida

William W. Thatcher, University of Florida

H. Allen Tucker, Michigan State University

Jeffrey Williams, Michigan State University

Sylvan Wittwer, Michigan State University

RESPONSE OF NATURAL ECOSYSTEMS TO CLIMATIC CHANGE

March 3-5, 1980
Rougemont, North Carolina

Thomas V. Armentano, The Institute of Ecology

Sandra Brown, Institute of Tropical Forestry

Patrick Coyne, U.S. Dept. of Agriculture, Woodward

Edward Farnworth, University of Georgia

John Hobbie, Woods Hole Marine Biological Laboratory

Jerry Olson, Oak Ridge National Laboratory

Hugo Rogus, North Carolina State University

Boyd R. Strain, Duke University

ECOLOGICAL CONSEQUENCES OF A CO2-INDUCED CLIMATE CHANGE ON FOREST ECOSYSTEMS

February 25-26, 1980
Blacksburg, Virginia

Alan Auclair, George Mason University

Kermit Cromack, Oregon State University

Sidney Gauthreaux, Clemson University

W. Frank Harris, Oak Ridge National Laboratory

W. Carter Johnson, Virginia Polytechnic Institute

Jerry Melillo, Woods Hole Marine Biological Laboratory

David M. Sharpe, Southern Illinois University

C. Richard Tracy, Colorado State University

RESEARCH NEEDED TO DETERMINE THE CARBON BALANCE IN NORTHERN ECOSYSTEMS AND THE POTENTIAL EFFECTS OF FUTURE INCREASED GLOBAL TEMPERATURES BY THE YEAR 2000

March 7-10, 1980
San Diego, California

John Andrews, University of Colorado

Dwight Billings, Duke University

Larry Bliss, University of Washington

Jerry Brown, U.S. Army Cold Regions Research and Engineering Laboratory

Charles F. Cooper, San Diego State University

Kaye Everett, Ohio State University

O.W. Heal, Merlewood Research Station, United Kingdom

David R. Klein, University of Alaska

Jochen Kummerow, San Diego State University

A.E. Linkins, Virginia Polytechnic Institute

Giles Marion, San Diego State University

Philip C. Miller, San Diego State University

Harvey Nichols, University of Colorado, Boulder

Walter Oechel, San Diego State University

Dennis Parkinson, University of Calgary

William Schlesinger, University of California, Santa Barbara

Gaius Shaver, Woods Hole Marine Biological Laboratory

Mjartmar Sveinbjornsson, Lunds Universitet, Sweden

Larry Tieszen, Augustana College

Keith Van Cleve, University of Alaska

Leslie Viereck, U.S. Forest Service, Fairbanks

Patrick Webber, University of Colorado, Boulder
Robert White, University of Alaska

RESEARCH ISSUES IN GRAZINGLANDS UNDER CHANGING CLIMATE

January 17, 1980 - Boulder, Colorado
February 10-11, 1980 - San Diego, California
March 6-7, 1980 - Denver, Colorado

Don Burzlaff, Texas Technological University

Gerald E. Carlson, U.S. Dept. of Agriculture, Beltsville

Dennis Child, Winrock International

Charles F. Cooper, San Diego State University

Robert Coupland, University of Saskatchewan, Canada

Patrick Coyne, U.S. Dept. of Agriculture, Woodward

Robert Dickinson, National Center for Atmpheric Research

Jerold L. Dodd, Colorado State University

Richard Eddy, Water and Power Resources Service, Denver

Harold Fritts, University of Arizona

Robert Gibbens, U.S. Dept. of Agriculture, Las Cruces

Harold Goetz, North Dakota State University

Leroy Hahn, U.S. Dept. of Agriculture, Clay Center

Tony Hall, University of California, Riverside

Jon Hanson, U.S. Dept. of Agriculture, Cheyenne

Richard H. Hart, USDA SEA-AR, Cheyenne

Min Hironaka, University of Idaho

Michael Horowitz, Institute of Developmental Anthropology

Carl James, Walter and Power Resources Service, Denver

Linda A. Joyce, Colorado State University

Will Kellogg, National Center for Atmospheric Research

Dennis Knight, University of Wyoming

William Lauenroth, Colorado State University

Roland Madden, National Center for Atmospheric Research

Dennis F. Pendleton, Colorado State Universty

Philip C. Miller, San Diego State University

R. Keith Miller, Bureau of Land Management, Washington, D.C.

William Parton, Colorado State University

Francisco Perez-Trejo, University of Llamos, Venezuela

Jean Reeder, U.S. Department of Agriculture, Fort Collins

Paul Risser, University of Oklahoma

Walter Orr Roberts, Aspen Institute for Humanistic Studies

David Robertshaw, Colorado State University

Rick Ross, U.S. Forest Service, Duluth

Edward J. Rykiel, Jr., Texas A & M University

Michael Schlesinger, Oregon State University

Stephen H. Schneider, National Center for Atmospheric Research

Jay Skiles, Colorado State University

Forrest Sneva, U.S. Dept. of Agriculture, Burns

Victor Squires, CSIRO, Australia

Jeffrey Ulrich, University of Wyoming

George M. Van Dyne, Colorado State University

Evan Vlachos, Colorado State University

Beatrice Willard, Colorado School of Mines

Gale Wolters, U.S. Forest Service, Washington, D.C.

Robert G. Woodmansee, Colorado State University

Terrance Yorks, Colorado State University

CLIMATE CHANGE AND AGRICULTURAL PRODUCTION
IN NON-INDUSTRIALIZED COUNTRIES

June 19-20, 1980
Oak Ridge, Tennessee

Wolfgang Baier, Land Resource Institute, Canada

Asit Biswas, Oxford, England

Thomas T. Cochrane, Centro International de Agricultura Tropica, Columbia

Robert Cowen, Christian Science Monitor

Milo Cox, University of Arizona

Richard Critchfield, journalist and consultant on Third World Villages

Ralph Cummings, Sr., Raleigh, North Carolina

Ralph Cummings, Jr., Rockefeller Foundation

Paulo de Tarso Alvim, CEPLAC, Brazil

Don Fiester, U.S. Agency for International Development

Robert Hagan, University of California, Davis

George H. Hargreaves, Utah State University

B.A. Krantz, University of California, Davis

H.N. Le Houerou, International Livestock Center for Africa

James Moomaw, International Agriculture Development Service

Ruperto Osorio, Ministry of National Resources, Honduras

Ned Raun, Winrock International

Roger Revelle, University of California, San Diego

Norman Rosenberg, University of Nebraska

Lloyd Slater, Aspen Institute for Humanistic Studies

Pierre Spitz, U.N. Research Institute for Social Development

EFFECTS OF CLIMATE CHANGE ON HUMAN AND ANIMAL HEALTH

March 23, 1980 - Chapel Hill, North Carolina
April 13, 1980 - Louisville, Kentucky

John Florin, University of North Carolina

Donald Heyneman, University of California, San Francisco

Melinda Meade, University of North Carolina, Chapel Hill

Jonathan Mayer, University of Washington

James Newman, Syracuse University

Robert Roundy, Rutgers University

Connie Weil, University of Minnesota

(Other Contributors to Commissioned Papers)

INFLUENCE OF SHORT-TERM CLIMATIC FLUCTUATIONS ON PERMAFROST TERRAIN

John T. Andrews, University of Colorado

Sue Ann Bowling, University of Alaska

Jerry Brown, U.S. Army Cold Regions Research and Engineering Laboratory

Richard Haugen, U.S. Army Cold Regions Research and Engineering Laboratory

David M. Hopkins, U.S. Geological Survey, Menlo Park

Arthur H. Lachenbruch, U.S. Geological Survey, Menlo Park

Samuel Outcalt, University of Michigan

Leslie Viereck, U.S. Forest Service, Fairbanks

A.L. Washburn, University of Washington

POTENTIAL EFFECTS ON OCEAN DYNAMICS OF
AN INCREASE IN ATMOSPHERIC CARBON DIOXIDE

Francis Bretherton, National Center for Atmospheric Research

Peter Brewer, Woods Hole Oceanographic Institution

Kirk Bryan, National Oceanic and Atmospheric Administration

Harry Bryden, Woods Hole Oceanographic Institution

Joseph Fletcher, National Oceanic and Atmospheric Administration

Theodore Foster, University of California, Santa Cruz

William Holland, National Center for Atmospheric Research

William Jenkins, Woods Hole Oceanographic Institution

Will Kellogg, National Center for Atmospheric Research

Henry Lansford, Boulder, Colorado

Michael McCartney, Woods Hole Oceanographic Institution

Albert Semtner, National Center for Atmospheric Research

EFFECTS OF INCREASED CO2 ON OCEAN BIOTA

Richard Barber, Duke University

Richard Dugdale, University of Southern California

Dale A. Kiefer, University Southern California

N. E. Tolbert, Michigan State University

EFFECTS OF INCREASED CO2 ON PHOTOSYNTHESIS AND AGRICULTURAL
PRODUCTIVITY

Basil Acock, Mississippi State University

L. Hartwell Allen, Jr., University of Florida

Donald N. Baker, Mississippi State University

Kenneth J. Boote, University of Florida

Dwight Camper, Clemson University

Harry F. Hodges, Mississippi State University

James W. Jones, University of Florida

Jerry R. Lambert, Clemson University

James M. McKinion, Mississippi State University

Virgil Quisenberry, Clemson University

Thomas Sinclair, University of Florida

Horace Skipper, Clemson University

Frank D. Whisler, Mississippi State University

IMPACTS OF RISING ATMOSPHERIC CARBON DIOXIDE LEVELS ON AGRICULTURAL GROWING SEASONS AND CROP WATER USE EFFICIENCES

D.M. Brown, University of Guelph, Ontario

R.W. Carlson, University of Illinois

H.Z. Enoch, Agricultural Research Organization, Israel

James E. Newman, Purdue University

H.H. Lamb, University of East Anglia, United Kingdom

E.R. Lemon, Cornell University

D.E. McCloud, University of Florida

D.M. Moss, Oregon State University

J. Olson, Oak Ridge National Laboratory

A.R. Pereira, Instituto Agronomico, Brazil

W.E. Reifsnyder, Yale University

N.J. Rosenberg, University of Nebraska

R.H. Shaw, Iowa State University

CO2-INDUCED CLIMATIC CHANGE AND ITS EFFECT ON PLANT PROTECTION

George Allen, U.S. Department of Agriculture, Washington, D.C.

Susan Battenfield, Michigan State University

George Bird, Michigan State University

Artie Browning, University of Iowa

Walter Conley, New Mexico State University

Thomas Edens, Michigan State University

Thomas Ellis, Michigan State University

Howard Ferris, University of California, Riverside

Winston Fulton, Michigan State University

Stuart Gage, Michigan State University

Dean Haynes, Michigan State University

Dave McKenzie, Pennsylvania State University

Fred Poston, Kansas State University

Alan Putnam, Michigan State University

Gene Safir, Michigan State University

Richard Sauer, University of Minnesota

Lal Tummala, Michigan State University

Steve Welch, Kansas State University

EFFECTS OF CO2-INDUCED CLIMATE CHANGE ON FRESHWATER ECOSYSTEMS

T.J. Blasing, Oak Ridge National Laboratory

Charles F. Cooper, San Diego State University

H. Doerksen, U.S. Fish and Wildlife Service

W.F. Harris, Oak Ridge National Laboratory

H.R. MacCrimmon, University of Guelph

P.J. Mulholland, Oak Ridge National Laboratory

D.E. Reichle, Oak Ridge National Laboratory

J.E. Richey, University of Washington

D.E. Stevens, California Department of Fish and Game

R.G. Stross, State University of New York, Albany

R.I. Van Hook, Oak Ridge National Laboratory

S. Watson, McGill University

M. Wunderlich, West German Federal Institute for Water Research

THE USE OF PALEOCLIMATIC DATA IN UNDERSTANDING AND POSSIBLY PREDICTING HOW CO2-INDUCED CLIMATIC CHANGE MAY AFFECT THE NATURAL BIOSPHERE

B. Berglund, University of Lund, Sweden

H.J.B. Birks, University of Cambridge, England

R. Brandley, University of Massachusetts

W.S. Broecker, Lamont-Doherty Geological Observatory

R.A. Bryson, University of Wisconsin

J. Grove, University of Cambridge, England

H. Nichols, University of Colorado

W.F. Ruddiman, Lamont-Doherty Geological Observatory

N. Shackleton, University of Cambridge, England

F.A. Street, University of Oxford, England

J. Thiede, University of Oslo, Norway

R.G. West, University of Cambridge, England

H.E. Wright, University of Minnesota

ANTHROPOLOGICAL PERSPECTIVES ON A CO2-INDUCED CLIMATE CHANGE

Elizabeth Colson, University of California, Berkeley

SOCIETAL IMPACTS OF AND RESPONSES TO CO2-INDUCED CLIMATE CHANGE; OPPORTUNITIES FOR RESEARCH

Philip O'Keefe, Clark University

William E. Riebsame, Clark University

Richard A. Warrick, Clark University

CLIMATE AND SOCIETY IN HISTORY: A RESEARCH AGENDA

Andrew Appleby, San Diego State University

Jan DeVries, University of California, Berkeley

David Fischer, Brandeis University

Milan Gutman, University of Texas, Austin

M.J. Ingram, The Queens University, Belfast

Ronald Lee, University of California, Berkeley

R.A. McDaniel, Purdue University

Christian Pfister, Geographiches Institute der Universitat Bern

John Post, Northeastern University

Theodore K. Rabb, Princeton University

Robert Rotberg, MIT

D.C. Smith, University of Maine

Lewis Steinberg, Princeton University graduate student

RESEARCH ON POLITICAL INSTITUTIONS AND THEIR RESPONSES TO THE PROBLEM OF INCREASING CO2

Dean Birch, University of California, Santa Barbara

Jack Corbett, Florida International University

J. Clarence Davies, The Conservation Foundation

Dean E. Mann, University of California

Lester Milbrath, State University of New York, Buffalo

INTERNATIONAL, LEGAL AND INSTITUTIONAL IMPLICATIONS OF AN INCREASE IN CARBON DIOXIDE

Michele Giusiana, Georgetown University law student

APPENDIX C

AAAS COMMITTEE ON CLIMATE

Roger Revelle, University of California, San Diego, Chairman

George E. Brown, Jr., U.S. House of Representatives

David Gates, University of Michigan

Robert Kates, Clark University

Nathan Keyfitz, Harvard University

J. Murray Mitchell, National Oceanic and Atmospheric Administration

William Nordhaus, Cowles Foundation for Research in Economics

Harry Perry, Resources for the Future

Dean F. Peterson, Agency for International Development

David Pimentel, Cornell University

Walter Orr Roberts, Aspen Institute for Humanistic Studies

Robert M. White, University Corporation for Atmospheric Research

David M. Burns, staff representative, AAAS

☆U.S. GOVERNMENT PRINTING OFFICE: 1980— 341-076: 1135