PREPARING FOR CLIMATE CHANGE

Proceedings of the First North American Conference on
Preparing for Climate Change: A Cooperative Approach
October 27-29, 1987 • Washington, D.C.

Honorary Co-Chairmen
Senator George Mitchell
Senator John Chafee

Convened by
Climate Institute • Washington, D.C.

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U.S. Department of Commerce, National Oceanic and Atmospheric Administration
U.S. National Climate Program Office (NOAA)
U.S. Department of Energy
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U.S. Department of Transportation, Maritime Administration
General Electric Foundation
National Parks and Conservation Association
BP America
American Gas Association
Ford Motor Company Fund
Adirondack Park Agency
World Resources Institute
United Nations Environment Programme

In Cooperation with Participating Agencies and Universities of the Canadian Climate Program
Attended by the delegation to the USA-USSR Bilateral for Environmental Cooperation

Government Institutes, Inc.

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TABLE OF CONTENTS

V. EARLY SIGNS OF GLOBAL WARMING?

VI. ANTICIPATING THE EFFECTS OF GLOBAL WARMING AND SEA LEVEL RISE ON COASTAL AREAS

VII. IMPACT OF CLIMATE CHANGE ON BIOLOGICAL DIVERSITY

VIII. ENERGY STRATEGIES AND CLIMATE CHANGE

IX. STRATOSPHERIC PROTECTION IN THE WAKE OF THE MONTREAL DIPLOMATIC CONFERENCE

X. SOCIETAL PLANNING FOR CLIMATE CHANGE

XI. PRESERVATION OF THE NATURAL ENVIRONMENT IN THE FACE OF RAPID CLIMATE CHANGE

XII. IMPACT OF CLIMATE CHANGE ON AIR QUALITY

XIII. IMPACT OF CLIMATE CHANGE ON WATER RESOURCES

XIV. IMPACT OF CLIMATE CHANGE ON NORTH AMERICAN AGRICULTURE

XV. IMPACT OF CLIMATE CHANGE ON THE GREAT LAKES REGION

APPENDIX

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PREFACE

Over the past decade a consensus has developed within the scientific community that the earth is about to enter an era of rapid climate change at a rate unprecedented in human history. The likely effects of such a dramatic global warming telescoped into a short time period may profoundly affect human institutions and the global environment. Yet, until very recently most government and private sector decisionmakers and planners have seemed to view greenhouse effect induced global warming as a problem for future generations.

In the summer of 1986 the Climate Institute was formed to bridge this gap between the scientific community and societal decisionmakers and opinion leaders. The Climate Institute was founded by a number of private citizens, several of whom had been leaders in the air pollution control field or research and policy arenas. The Institute's founders who included senior officials in the last four Presidential Administrations have sought to bring climate change onto the public agenda without having the discussion become polarized.

From its conception by Paul C. Pritchard, the Institute's first Chairman, The First North American Conference on Preparing for Climate Change: A Cooperative Approach was designed to enlist a broad range of sponsors and participants from throughout North America. Ultimately, the conference's sponsors included seven U.S. government agencies, five corporate sector institutions, three environmental policy or research institutions, a state government agency and the United Nations Environment Programme. In addition, the Canadian Climate Program, which has been at the cutting edge of research and policy analysis on impacts of climate change, actively recruited a strong assemblage of Canadian presenters.

The conference was the beneficiary of remarkable serendipity. The signing during mid-September 1987 in Montreal, Canada of the UNEP Protocol on Substances that Deplete the Ozone Layer fostered hope that cooperative international action might be possible to address the challenge of a rapidly enhanced greenhouse effect. The disclosure in late September that springtime ozone levels over Antarctica had fallen in 1987 to levels much lower than ever previously recorded added a sense of urgency to the discussions. A cover story in the October 19, 1987 edition of Time drew heavily on interviews with conference panelists to convey the significance of the greenhouse effect and Antarctic ozone problems. This helped to ensure the attendance of about 300 conference participants.

Perhaps, the most remarkable element was provided by the attendance and active participation of a four-person Soviet delegation. This delegation to the USA-USSR Bilateral for Environmental Cooperation was headed by Dr. Mikhail Budyko, one of the world's most highly respected climatologists. The Soviet participation, together with that of the United Nations Environment Programme, the World Bank and several European embassies, helped to add a global dimension to discussions which centered on effects of climate change on North America.

The imminence of the Reagan-Gorbachev Summit provided a focus for moves to elevate climate change onto the international agenda. Senator John Chafee in his speech at the Awards Dinner opening the conference reiterated his call for placing of climate change on the Summit agenda. Six weeks later the world climate community was delighted to see joint U.S.-Soviet cooperation on global climate issues become a prominent part of the Reagan-Gorbachev communique. The text of this statement is provided in the Introduction by Dr. Alan Hecht whose efforts contributed significantly to the fostering of close U.S.-Soviet cooperation on global climate issues.

The positive outcome of the conference was also attributable to the success of the agenda in breaking the discussions into chewable pieces. Too often policy discussions of the greenhouse effect have foundered on a perception that the enormity of the problem makes any individual response hopelessly inadequate. This belief tends to delay formulation and implementation of incremental response and adaptation strategies while discussions focus on a "magic wand" solution. This conference instead explored practical means of limiting greenhouse gas emissions and simultaneously constructing strategies to adapt to and mitigate the adverse effects of the likely global warming.

There is mounting evidence that the rapid climate change predicted by the world's leading climate modelers may already be upon us. 1987 was the warmest year in the history of instrumental records according to a January 1988 article by

James Hansen and Sergej Lebedeff of NASA's Goddard Institute for Space Studies.

The publication of these proceedings will, we anticipate, stimulate further discussions of workable response strategies to the challenge posed by rapid climate change.

In consequence of a cooperative agreement between the U.S. Environmental Protection Agency and the Climate Institute, an ambitious series of seminars is scheduled to examine in depth the impact of climate change on areas vital to our environment or our economy. A Symposium on the Impact of Climate Change on Commercial and Sport Fishing in North America was held in October 1987, and a Symposium on the Impact of Climate Change on Wildlife was convened in January 1988. In forthcoming months seminars are planned on the Impact of Climate Change on the Third World and the Implications for Development Assistance, the Implications of Climate Change for Municipal Infrastructure Planning and the Implications of Climate Change for Private Sector Investment. These deliberations, we anticipate, will result in publications of interest to planners and decisionmakers in these respective areas.

Building on these seminars and the success of the October 1987 conference, the Climate Institute is planning to convene a Second North American Conference on Preparing for Climate Change later this year. This meeting will probe in much greater detail such concerns as the impact of climate change on wildlife, forests, and coastal resources, the potential impact of Arctic emissions in enhancing global warming, and the potential effects of climate change on such fragile ecosystems as the Chesapeake Bay.

John C. Topping, Jr.
President
Climate Institute

INTRODUCTION

PLANNING FOR CLIMATE CHANGE

Summary of Remarks by

Dr. Alan Hecht
Director, National Climate Program Office
Office of the Chief Scientist/NOAA

As society faces the next decades, it will deal with several major environmental and social issues. For example, increased population growth, especially in the developing world, is likely to continue and stress environmental and social resources. Drought, famine, the spread of disease and environmental degradation in Africa, South America and elsewhere, affect, through the complex political and economic web of society today, all nations.

In the decades ahead there may be major environmental changes as well. There is now a heightened sense of awareness among many nations of the global nature of environmental problems. Acid rain, ozone depletion and climate change are no longer local or academic issues. Ozone depletion and future climate change are becoming critical factors in political and economic decisionmaking.

The international protocol on the control of chlorofluorocarbons (CFC's) is a major achievement in the collective efforts of man to balance economic growth and environmental management. A greater challenge ahead is to deal with the more difficult subject of future climate change.

The prospect of future climate change, largely due to man-induced changes in the chemical composition of the atmosphere, is almost too difficult to comprehend. The atmosphere and oceans are so vast that it is almost unimaginable that man-made gases would not be absorbed, diluted and dissipated. But just the opposite is true. Since the industrial revolution in the middle of the last century, the burning of fossil fuel has steadily increased resulting in an ever increasing atmospheric concentration of carbon dioxide.

The CFC's are also increasing, along with methane, nitrous oxide, sulphur dioxide and other minor gases. Some of these gases are naturally produced, but the greatest concentration of them results from man-made activities. Despite the vastness of the atmosphere and ocean, they remain there, trapped for many years, before breaking down into something else.

We can predict how these gases will affect the atmosphere from theoretical and numerical modeling experiments. For example, for a doubling of carbon dioxide content, a global warming of somewhere between 2-4 degrees Celsius is projected. The warming is not uniformly distributed over the surface of the earth, rather it is expected to be nearly three times as great in high latitude areas than in the tropics. What such a climate change means for specific regions, such as the Great Lakes Basin, the grain growing areas of the United States or the Soviet Union, or for Washington, DC is not known, nor may it be possible to determine in the decade ahead. Numerical modeling capabilities are largely insufficient to make such regional predictions.

The observed climate records of the atmosphere, such as temperature and sea level, have not yet confirmed the expected global warming. By confirmed, I mean to distinguish a clear signal in changing climate from the natural noise of variability. Climate changes due to natural causes as well. The "smoking gun," a popular Washington phrase, in climate has not yet been found.

Despite the uncertainties which exist, and which will not be significantly reduced in the next decade, there is ample reason to take seriously the expected climate change and begin to plan accordingly. It must now be recognized that there is substantial risk of a possible future climate change. These risks must be considered in future environmental, economic and social planning.

This realization does not lead to a major upheaval in the global energy production. Rather it points to the need for developing certain environmental and economic strategies which aim at minimizing future risks by expanding management options at this time. For example, such strategies might include measures aimed at improving the conservation and efficiency of energy use thus mitigating any global change. All change may be costly, but some change may be more costly than others. Delaying such change and at the same time increasing energy efficiency may serve both economic and environmental needs. Major efforts to seek alternate energy sources may further reduce the potential magnitude of future climate change.

Climatologists face a tremendous challenge. Political and industrial leaders look to them for answers to almost impossible questions. Yet, the non-physical scientists, even given answers, may themselves not be able to respond. After all, how solid is understanding of the adaptability of existing social and economic systems to a climate change? At what point will these systems be stressed? Are existing management tools and legislation adequate to regulate surface and ground water in the United States to meet climate changes? What is the possible cost to agriculture for increases in temperature and decreases in precipitation in the mid-west of the United States? What will a more favorable climate mean to the Soviet Union and its relationships with the rest of the world?

There are a number of social and economic questions which should be addressed at the same time as physical scientists try to predict future climates. Adequate policymaking will require both sets of information. It is not too soon to begin to assess the full range of possible economic and social responses to a changing climate and to develop national policies. Combined efforts of social, political and physical scientists are needed.

It is fortuitous that concurrent with this meeting, the United States and the Soviet Union have just concluded new agreements to cooperate in studies of ozone depletion and future climate. Our activities are carried out under the USA-USSR Bilateral for Environmental Protection. Under this agreement there is a working group on climate. The USA and USSR co-chairmen are myself and Dr. Mikhail Budyko, who is participating in this conference.

Dr. Budyko is one of the founders of the field of climatology. He has made significant contributions to climate modeling and is responsible for organizing climate studies in the Soviet Union. We are happy to welcome him and other members of the Soviet delegation to this meeting. Our work of this week has resulted in a program of cooperation between our two countries which recognizes the importance of climate change as an international issue.[1],[2]

[1] Note added in Proof: The importance of the cooperation in climate research between the two countries was highlighted in the joint communique from the Reagan-Gorbachev Summit:

> **With reference to their November 1985 Agreement in Geneva to cooperate in the preservation of the environment, the two leaders approved a bilateral initiative to pursue joint studies in global climate and environmental changes through cooperation in areas of mutual concern, such as protection and conservation of stratospheric ozone, and through increased data exchanges pursuant to the U.S.-Soviet Environmental Protection Agreement and the Agreement between the United States of America and the Union of Soviet Socialist Republics concerning cooperation in the exploration and use of outer space for peaceful purposes. In this context, there will be a detailed study on the climate of the future. The two sides will continue to promote broad international and bilateral cooperation in the increasingly important area of global climate and environmental change.**

[2] Members of the Soviet Delegation in attendance were:

Mikhail Budyko
State Hydrologic Institute/GOSKOMGIDROMET

Sergei Khmelevtsov
Institute of Experimental Meteorology/GOSKOM

Veniamin Lobanov
GOSKOM

Konstantin Vinnikov
State Hydrologic Institute/GOSKOM

ACKNOWLEDGMENTS

This conference was launched at the initiative of Paul C. Pritchard, President of the National Parks and Conservation Association and first Chairman of the Climate Institute. Besides conceiving the theme for this watershed conference, he brought together the critical mass of resources and organizational talent to make it a success.

Senator George Mitchell and Senator John Chafee, the Honorary Co-Chairmen of the Conference, have provided continuing leadership in the U.S. Congress on climate change issues as well as stirring addresses to the First North American Conference on Preparing for Climate Change: A Cooperative Approach.

Dr. Alan Hecht, Director of the U.S. National Climate Program, served as the federal program lead for multi-agency funding of this endeavor. In addition, as the U.S. lead in the USA-USSR Bilateral for Environmental Cooperation, he was instrumental in attracting to the conference a Soviet scientific delegation headed by Dr. Mikhail Budyko. Alan Malinauskas, Acting Head of the Canadian Climate Program, helped us assemble a strong array of Canadian presenters.

We are indebted to numerous organizations and individuals for their help in funding this conference, especially to Ted Williams of the U.S. Department of Energy, Jack Talmadge of the National Science Foundation, Bob Watson of NASA, Dick Morgenstern, Dennis Tirpak and Joel Smith of EPA, Randy Hanchey of the U.S. Army Corps of Engineers and Dan Leubecker of the Maritime Administration. For our wide range of non-federal support we are especially grateful to Roger Strelow of the General Electric Company, Nelson Hay of the American Gas Association, Bob Malone of BP America, Helen Petrauskas and Bill King of Ford Motor Company, Woody Cole of the Adirondack Park Agency, Rafe Pomerance of the World Resources Institute, and Dr. Mostafa Tolba, Dr. Michael Gwynne and Joan Martin-Brown of the UN Environment Programme.

We appreciate the work of our conference committee, especially that of its Chairman, Dr. Charles Powers, and of Tom Magness. The work of our conference management consultant, Hartnett & Associates, was exemplary and we are especially grateful to Cathie Hartnett, Dan Barry, Cindy Kunz, Emily Saltzman and Debbie Dill. Nancy Wilson and Joan Elzery were instrumental in ensuring wide press attention to the proceedings. Melissa Hester of the Climate Institute staff played a vital role in ensuring the success of the conference.

Jim Dyer has performed a remarkable job in preparing the proceedings for publication. We also appreciate the efforts of Dave Williams and Charlene Ikonomou of Government Institutes, Inc. in ensuring timely publication of these proceedings.

CONFERENCE SPONSORSHIP

This conference is organized by the Climate Institute with the generous support and cooperation of:

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AGENDA

October 27
Tuesday Night

CLIMATE INSTITUTE AWARDS RECEPTION AND DINNER
6:00-7:00 p.m.--Reception
7:00-9:30 p.m.--Dinner

Presentation of awards to individuals or institutions that have advanced public understanding of climate change.

Welcoming remarks of Conference Convenor **Paul Pritchard**, President of the National Parks and Conservation Association and Chairman of the Climate Institute.

Recognition of UNEP Stratospheric Protection Agreement--**Rafe Pomerance**

Report from Montreal
Ambassador Richard Benedick
Chief U.S. Negotiator, UNEP Chlorofluorocarbon Conference

Greetings from the international scientific community by **Dr. Mikhail Budyko**, GOSCOMGIDROMET, USSR.

Description of Awards, **Roger Strelow, Esq.** Chairman, Awards Committee.

Presentation of Award to **Dr. Roger Revelle** for outstanding scientific achievement in the climate field by **Dr. Stephen Leatherman.**

Presentation of Award to **Senator John Chafee** for outstanding work in advancing public understanding of the challenges posed by climate change.

Address
Senator John Chafee

October 28
Wednesday Morning

WHAT WE KNOW ABOUT THE EVOLUTION OF OUR GLOBAL CLIMATE. WHAT CAN DECISIONMAKERS RELY UPON?

Dr. Stephen Schneider, National Center for Atmospheric Research
"The greenhouse effect--what we can or should do about it."

Dr. Alan Hecht, Director, U.S. National Climate Program Office
"An overview of the U.S. effort to address the likely implications of climate change."

J.A.W. McCulloch, Director General, Canadian Climate Centre
"The Canadian Climate Program."

Dr. James Hansen, Director, Goddard Institute for Space Studies
"What we can predict about the likely pace and regional implications of global warming."

Dr. Robert Watson, Director, NASA Upper Atmospheric Program
"What do we know about stratospheric change?"

Dr. Mikhail Budyko, Discussion of USA-USSR Bilateral for Environmental Cooperation

Luncheon Speaker
12:00-1:30 p.m. (Ballroom)
Howard Ferguson, Head, The Atmospheric Environment Service, Canada

FOUR SIMULTANEOUS PANELS

GLOBAL ASPECTS OF THE CLIMATE CHANGE CHALLENGE

Potential Early Signals of Climate Change: Global and Polar

1:45-3:30 p.m.

Moderator

Dr. Roger Revelle, University of California, San Diego

Panelists

Dr. Arthur Lachenbruch, U.S. Geological Survey
"Warming of the permafrost in Northern Alaska."

Dr. Gordon MacDonald, Vice President and Chief Scientist, MITRE Corporation
"Potential of methane hydrates to enhance global warming."

Dr. Claire Parkinson, NASA Goddard Space Flight Center
"Sea ice as a potential early indicator of climate change."

Dr. Stephen Schneider, National Center for Atmospheric Research
"What would a greenhouse warming look like and how would we know it?"

Tropical Rain Forest Preservation: An Ecological and Political Challenge

Moderator

Dr. William Nagle, World Resources Institute

Panelists

Dr. George Woodwell, Director, Wood's Hole Research Center
"Interaction of warming with biotic resources."

William Burley, Sr., Director, Tropical Forestry Project, World Resources Institute
"How we can preserve our tropical forests."

John Spears, World Bank
"Role of international financial institutions in tropical forest preservation."

Anticipating the Effects on Coastal States Global Warming and Sea Level Rise

Moderator

John McGlennon, President, ERM McGlennon

Panelists

Jim Titus, Director, EPA Sea Level Rise Project
"Likely effects and extent of sea level rise."

Dr. Stephen Leatherman, Director, Laboratory for Coastal Research, University of Maryland
"Effects of sea level rise on beaches and coastal wetlands."

Robert Whalin, Technical Director, U.S. Army Waterways Experiment Station, Vicksburg, MS
"Strategies to protect coastal structures."

Dr. Tom Goemans, Director SIBAS, Delft, The Netherlands
"Low countries and high seas."

Dr. Dail Brown, NOAA
"Factoring sea level rise projections into coastal zone management."

Likely Effect of Climate Change on Biological Diversity

Moderator

Dr. Robert Peters, World Wildlife Fund/Conservation Foundation

Panelists

Dr. Sylvia Edlund, Geological Survey of Canada
"Effects of climate change on Arctic vegetation."

Dr. C.R. Harington, National Museums of Canada
"Past effects of climate change on Arctic vertebrates."

Dr. Margaret Davis, University of Minnesota
"Effects of climate change on temperate zone forests."

FOUR SIMULTANEOUS PANELS

CLIMATE CHANGE: THE NORTH AMERICAN RESPONSE

3:35-5:30 p.m.

Energy Use Strategies and Climate Change: Should They Go Beyond Conservation?

Moderator

Edward Williams, Director, Office of Environmental Analysis,
U.S. Department of Energy

Panelists

Dr. Gordon MacDonald, Chief Scientist, MITRE Corporation
"Impact of energy strategies on climate change."

Dr. Irving Mintzer, Sr., World Resources Institute
"Energy strategy options and climatic effects."

Dr. Ali Cambel, George Washington University
"Potential of superconductors to limit growth of greenhouse gas emissions."

Dr. Frederick Koomanoff, Director, DOE Carbon Dioxide Research Division
"Energy use trends and climate change."

Stratospheric Protection in the Wake of the Montreal Diplomatic Conference

Moderator

Craig Potter, Esq., Assistant Administrator for Air and Radiation, U.S. EPA

Panelists

Dr. F. Sherwood Rowland, University of California, Irvine
"Potential of heterogeneous chemistry to enhance predicted levels of ozone depletion."

John Hoffman, Director, EPA Stratospheric Protection Program
"Health and ecological considerations in CFC regulation."

David Doniger, Esq., National Resources Defense Council
"Outlook for further domestic and international regulation of chlorofluorocarbons."

Dr. Mack McFarland, Fluorocarbon Program Panel of the Chemical
Manufacturers Association, "Stratospheric ozone projections in light of the
UNEP scenarios."

Richard Barnett, Chairman, Alliance for a Responsible CFC Policy
"Ensuring fair implementation of the UNEP agreement."

Societal Planning for Climate Change: How Can the Public and Private Sectors Adapt?

Moderator

Roger Strelow, Esq., Vice President, General Electric

Panelists

Dr. Peter Stokoe, Dalhousie University
"Effects of climate change on fisheries, aquaculture, shipping and offshore oil drilling in the Atlantic."

Dr. Charles W. Powers, Resources for Responsible Management, Inc.
"Adjusting hazardous waste management strategies to allow for sea level rise and climate change."

Dr. Richard Morgenstern, Director, Office of Policy Analysis, U.S. EPA
"How should we adjust environmental decisionmaking to accommodate prospective climate change?"

William F. Pedersen, Jr., Esq., Verner, Liipfert, Bernhard, McPherson & Hand
"Does NEPA already require weighing of climate change impact?"

Dr. Ken Linder, Vice President, ICF
"Implications of climate change for electric utility planning."

Wildlife, Fish, Forests and Parks: How Can We Preserve the Quality of Our Environment in the Face of Rapid Climate Change?

Moderator

Elizabeth Fayad, National Parks and Conservation Association

Panelists

Rev. Herman Cole, Chair, Adirondack Park Agency
"Park preservation strategies in a warming world."

Dr. Henry Regier, University of Toronto
"Likely effects of climate change on wetlands and fisheries."

Dr. Carl Winget, Director General, Research and Technical Services Directorate, Canadian Forestry Service, "Forest management strategies to address climate change."

7:00 p.m. Reception for Panelists
220 Maryland Avenue, N.E.

October 29
Thursday Morning
Continental Breakfast
Panel Discussion: **Congressmen George E. Brown, Jr. and Bill Green**

FOUR SIMULTANEOUS PANELS

MITIGATING THE EFFECTS OF CLIMATE CHANGE

9:50-11:45 a.m.

Global Warming, Stratospheric Modification, Ground Level Ozone and Acid Rain: How Will Their Interaction Affect Air Quality?

Moderator

Thomas Grumbly, President, Clean Sites, Inc.

Panelists

Dr. F. Sherwood Rowland
"Effects of changes in atmospheric and stratospheric chemistry on air quality."

Dr. Gary Whitten, Systems Applications, Inc.
"Stratospheric ozone modification and ground level ozone."

John Bachmann, Office of Air Quality Planning and Standards, U.S. EPA
"Likely effects on air quality of projected global warming."

Dr. Michael Oppenheimer, Environmental Defense Fund
"Likely ecological effects of these changes."

Dr. Devra Davis, National Academy of Sciences
"Health implications of climate induced changes in air quality."

Climate Change in the Great Lakes Region: How is it Likely to Transform the Economy and the Environment?

Moderator

Professor Dean Abrahamson, Hubert Humphrey Institute
of Public Affairs, University of Minnesota

Panelists

Dr. Stewart Cohen, Canadian Climate Centre
"How climate change in the Great Lakes Basin may affect energy, hydrology, shipping and recreation."

Dr. Barry Smit, University of Guelph
"Likely effects of climate change on agriculture in the Great Lakes Basin."

Dr. Frank Quinn, NOAA
"Likely effects of climate change on water levels in the Great Lakes."

Joseph Raoul, U.S. Army Corps of Engineers
"Likely effects of climate change on Great Lakes navigation."

Climate Change and North American Agriculture: How Can We Adapt?

Moderator

Dr. Cynthia Rosenzweig, Columbia University

Panelists

Dr. R.B. Stewart, Agriculture Canada
"Implications of climate change for agricultural productivity in the North American Prairies."

Dr. Norman Rosenberg, Resources for the Future
"Likely effects of climate change on the U.S. Farm Belt."

Dr. Louise Arthur, University of Manitoba
"Likely impact of climate change on the North American agricultural community."

Dr. Daniel Dudek, Senior Economist, Environmental Defense Fund
"Economic consequences of change in climate on North American agriculture."

Dr. Stephen L. Rawlins, U.S. Department of Agriculture
"Strategies for adapting agriculture to adjust to climate change."

Climate Change and Water Availability

Moderator

Joseph Cannon, Esq., Pillsbury, Madison & Sutro

Panelists

Dr. David Rind, Goddard Institute for Space Studies
"Likely effects of global warming on water availability and hydrology in North America."

James Strock, Esq., Davis, Graham & Stubbs
"Adjusting water allocation law to meet water quality and availability concerns in a warming world."

Dr. Edward Dickey, Deputy for Programs, U.S. Army Civil Works
"Water resource development problems and opportunities related to climate change."

Kyle Schilling, Institute for Water Resources, U.S. Army Corps of Engineers
"Building hydrologic risks and uncertainties related to climate change into water resource planning."

Thursday Luncheon

Panel discussion on the Antarctic Ozone Phenomenon including **Dr. Robert Watson**, NASA, **Dr. F. Sherwood Rowland**, University of California, Irvine, and **Dr. Adrian Tuck** of NOAA

FISHERIES SYMPOSIUM

Immediately following the conclusion of the conference, the Climate Institute inaugurated its Climate Impact Seminar Series with a day and a half symposium on the "Impact of Climate Change on Commercial and Sport Fishing." This symposium was held at the conference site from 2:30 p.m., October 29, to about 3:30 p.m., October 30. Canadian and U.S. fisheries experts assessed the impact of global warming, sea level rise, increased ultraviolet radiation and El Nino on North American fisheries. Subsequent seminars will explore the implications of climate change for wildlife, municipal infrastructure investment, international development assistance, private sector investment, and air pollution control. The U.S. Environmental Protection Agency is a co-sponsor of this seminar series.

AGENDA

October 29, 1987
Thursday

2:30-5:00 p.m.

A. Alan Hill, Chairman, Council on Environmental Quality
"Climate change and environmental planning: An American view."

Jim Titus, Strategic Studies Staff, U.S. EPA
"Implications of climate change for fisheries management."

Dr. Robert C. Worrest, Oregon State University
"Implications of increased UVB for fisheries."

October 30, 1987
Friday

9:00 a.m.-3:30 p.m.

Dr. Peter Stokoe, Dalhousie University
"Impact of climate change on North Atlantic fisheries."

Dr. Edward LaRoe, National Fish & Wildlife Service
"Gulf Coast wetlands loss and its fisheries impact"

Dr. Henry Regier, University of Toronto
"Impact of climate change on Great Lake fisheries."

Luncheon
12:00-1:30 p.m. (Ballroom)

Dr. Skip Livingston, Florida State University
"Impact of climate change on yields of estuarine fisheries."

Dr. Thomas Sibley, University of Washington
"Impact of climate change on North Pacific and Alaskan Fisheries."

AWARDS TO DR. ROGER REVELLE AND SENATOR JOHN CHAFEE

In 1987 the Climate Institute initiated annual awards to be given in each of two categories, the first for scientific achievement increasing our knowledge of global climate change and the second for advancing public understanding of the challenge posed by climate change.

An Awards Committee consisting of members of the Climate Institute's Board of Directors sought the advice of prominent scientists and others knowledgeable about global climate issues. Roger Strelow, Vice President for Corporate Environmental Programs of General Electric, chaired the Committee which also included Dr. Stephen Leatherman, Director of the Laboratory for Coastal Research of the University of Maryland, Rafe Pomerance, Senior Associate of the World Resources Institute, Paul C. Pritchard, Chairman of the Institute's Board and President of the National Parks and Conservation Association, and John C. Topping, Jr., President of the Climate Institute. After receiving the recommendations of its Awards Committee, the Climate Institute Board unanimously chose Dr. Roger Revelle and Senator John Chafee as the first two recipients of its annual awards.

Dr. Revelle was cited for outstanding scientific achievement in furthering knowledge of the global climate system.

"Dr. Revelle is widely regarded as both the leading oceanographer and climatologist in the world during the past generation," according to the Climate Institute.

Dr. Revelle, who currently heads the Committee on Climate of the American Association for the Advancement of Science, has performed research and analysis of many aspects of the problem of greenhouse effect induced global warming. His groundbreaking work concerns issues such as probable future changes in sea level resulting from increased atmospheric carbon dioxide, effects of global warming on water supplies in the Western United States, the role of the methane hydrates in increasing global warming and effects of the El Nino/Southern Oscillation on the atmospheric content of carbon dioxide.

Senator Chafee was selected for his achievements in advancing public understanding of the challenges posed by greenhouse effect induced global warming and stratospheric ozone depletion.

"The two day Senate hearings on the greenhouse effect and stratospheric ozone depletion convened and chaired by Senator Chafee were a watershed in focusing public attention on these issues and building the consensus for the historic breakthrough in the UNEP stratospheric protection negotiations," the Climate Institute said in announcing the award.

Senator Chafee's efforts resulted in the initiation of the studies of the greenhouse effect and policy options to limit its increase by the U.S. Environmental Protection Agency, the National Academy of Sciences, and the Office of Technology Assessment of the U.S. Congress, according to the Institute.

Both Dr. Revelle and Senator Chafee were honored October 27, 1987 at the Awards Dinner kicking off the Conference. Senator Chafee provided the principal address at the dinner and Dr. Revelle presided the next day at a panel on Early Signals of Climate Change.

The awards given to Dr. Revelle and Senator Chafee consisted of plaques to each of which was attached a drill bit used in the first ice coring ever done on the Tibetan Plateau. The drill bits were provided to the Climate Institute by the University of Nebraska Ice Coring Project.

RECOGNITION OF UNEP STRATOSPHERIC PROTECTION AGREEMENT

Remarks of

Rafe Pomerance
Member of Climate Institute Board
and
Senior Associate, World Resources Institute

Tonight, the Board of Directors of the Climate Institute decided to recognize a major political and scientific accomplishment that was announced just two weeks ago and that bears directly on what we are discussing tonight and over the next two days--that achievement is the Montreal Protocol on Substances that Deplete the Ozone Layer.

When I say this, I want to remind you that the topic of this conference is, "The First North American Conference on Preparing for Climate Change: A Cooperative Approach." This achievement of Montreal reflects that same theme of this conference--cooperation.

Let me say a word about how this theme of the cooperative approach--how it will be tested in the future and how we must hope that this approach can be sustained in the face of other challenges to the functioning of planetary systems.

First, the adequacy of the Montreal agreement will be challenged--it was challenged today on a Senate hearing because of the emerging data on Antarctica. Montreal is a great achievement, but not sufficient if today's hearing is an indication of what is going on over Antarctica.

Second, trying to deal with the greenhouse effect may dwarf the achievements to date on ozone depletion.

Tonight, we take note of the great international achievement that Montreal represents and acknowledge the participants who made it possible.

Most important, we wanted to be sure that the leadership provided by the United Nations Environment Programme--that small international agency in Nairobi--was fully recognized.

In particular, we want all who are here to recognize that without the sustained and visionary leadership of Dr. Mostafa Tolba and his staff at UNEP--including Joan Martin-Brown in the United States--this agreement could not have been achieved. The Montreal Protocol was a great triumph for UNEP as an institution.

We want to be sure that we acknowledge the role of political leaders, environment ministers, and non-government organizations from the many countries around the world--those who sat through hours of negotiations over the many months and in the many cities to arrive at an agreement. The European Economic Community, Japan, the Soviet Union, Scandinavian countries, the Canadians and many developing countries--all played a positive and constructive role during the process.

We also want to be sure that we recognize all those in the United States who helped bring this about. We say thank you to:

- The Members of Congress including Senator Chafee, who is here with us tonight.
- The leadership of the State Department including Ambassador Richard Benedick, who was so instrumental in the activities surrounding the Montreal Protocol.
- The Administrator of the U.S. Environmental Protection Agency, Lee Thomas, and his dedicated and talented staff--particularly John Hoffman and Steve Seidel for their dedicated work over many years.
- Independent scientists who warned us long ago about this problem--including Sherry Rowland, who is with us tonight.
- Government scientists from the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the National Science Foundation--Bob Watson and Dan Albritton, who served on the U.S. delegation who deserve our thanks.
- Non-governmental organizations, such as the Natural Resources Defense Council, the Environmental Defense Fund, Friends of the Earth and World Resources Institute--all of whom followed the negotiations closely.
- Industry leaders who have participated in both the scientific and policy discussions and urged a global agreement.

To all of you who gave so much in Rome, Geneva, Brussels, Vienna and Montreal--over these many months--may we say, "Thank you."

Report from Montreal: A Landmark Global Treaty to Protect the Ozone Layer

Ambassador Richard Elliot Benedick

Principal U.S. negotiator for the ozone treaty and Deputy Assistant Secretary of State; curently on detail from the State Department to The Conservation Foundation.

On September 16 in Montreal, representatives of 24 nations from every region signed a treaty to limit production and consumption of several chemicals which are believed to cause virtually irreversible damage to the fragile stratospheric ozone layer. Among the signatories were almost all of the world's major producer and consumer countries. In addition, other nations among the nearly 50 in attendance indicated that they would probably join in the coming months.

The accord provides for a near-term freeze, followed by scheduled reductions, in use of several chlorofluorocarbon (CFC) and bromine (halon) compounds. Depletion of the ozone layer caused by these man-made chemicals would result in increased ultraviolet radiation reaching the earth's surface, with potentially significant adverse implications for human, animal and plant life. In addition, CFCs have the qualities of a "greenhouse gas," thus contributing to the global warming trend and the resulting dangers for agriculture and rising sea levels. Against these risks were weighed the costs of replacing chemicals useful in refrigeration, air conditioning, plastics, insulation, aerosol sprays, fire fighting and computers.

Several features of the Montreal treaty, and the process by which it was achieved, mark it as an historic accomplishment with important lessons for future international environmental cooperation. First, it was unprecedented for the global community to impose controls on an important industrial sector <u>before</u> actual damages to human health and ecology were registered. This was not a response to an environmental disaster, such as Chernobyl or the Rhine River spill. Rather, it was a conscious preventative action, on a global scale, which involved several years of collaborative scientific research and analysis, and arduous intergovernmental negotiations to reconcile numerous diverse and conflicting interests.

Second, the treaty could never have been accomplished without the closest cooperation between government policy makers and the international scientific community, working at the frontiers of modern science. Only relatively recent--and still evolving--advances in computer modelling of atmospheric chemistry and satellite measurement of ozone and trace gases could enable governments to undertake costly controls in advance of actual recorded damages. (It is worth noting that the widely publicized "hole" in the ozone layer over the South Pole was not factored into the negotiations because of the lack of evidence that this phenomenon could occur outside of the unique Antarctic climate.)

Third, in the face of remaining uncertainty concerning the extent both of future ozone depletion and of potential deleterious effects, the parties undertook a unique process of risk assessment. Government officials, scientists, and representatives of industry and environmental groups met as individuals in a series of informal workshops, without predetermined national positions. To a degree that surprised even many participants, this innovative process was able to achieve a cooperative spirit and a degree of consensus even before the actual negotiations began. The treaty negotiations themselves covered only four formal sessions in the ten-month period from December 1986 to September 1987. Considering the complexity of the issues involved--political, environmental, economic, scientific, technological, trade, geographical--this was an impressive achievement.

Fourth, The United Nations Environment Program (UNEP) played a critical role in this process. This small UN agency, with an annual budget of less than $40 million, sponsored the workshops and negotiations, and provided an objective international forum without the extraneous political debate that has so often marred the work of other UN bodies. The political sensitivity and diplomatic skills of UNEP's Executive Director Mostafa Tolba, himself a scientist, were indispensable during the often hard negotiations. UNEP was the very model of how a UN agency should function.

Fifth, the leadership role of the United States, which had as early as 1978 undertaken major controls on CFCs, and which is the center for scientific research on this subject, was a major factor. Especially during the period from the fall of 1986 through the spring of 1987, a series of diplomatic initiatives, bilateral scientific and policy missions, and use of international media, all served to reach foreign policy makers and publics--which in some countries were initially hostile or indifferent--with the rationale for the U.S. position. The treaty as eventually signed was, in fact, based upon the structure and concept initally advanced by the United States late last year.

The U.S. private sector and Congress made important contributions to the process. U.S. environmental groups helped inform foreign public opinion of the dangers of ozone layer depletion, while American industry was far ahead of European and Japanese producers in acknowledging its responsibility and supporting further controls on both CFCs and halons. And the U.S. Congress, through hearings, resolutions, and proposed legislation, served notice to the rest of the world that if an acceptable international accord were not attained, it was prepared to legislate unilaterally, with trade restrictions against countries not accepting their share of this global responsibility.

While the Montreal treaty is not perfect, and will require further technical and legal clarification, it does represent a prudent international insurance policy in response to a very complex set of issues and uncertainties. An important innovation is the firm schedule for reductions in consumption and production of the controlled chemicals, which provides clear market incentives to industry to develop new technologies and substitute products. (In this connection, The Conservation Foundation, together with EPA and Environment Canada, is co-sponsoring a conference and trade fair in January 1988 on substitutes and alternatives to CFCs and halons.) Another significant element of the treaty is that it is crafted as a dynamic instrument, which can be adapted to changing conditions, such as implications of the still emerging scientific evidence on the Antarctic ozone "hole". In sum, in undertaking collaborative preventative action to protect future generations from potential dangers, the nations represented at Montreal charted new paths in environmental cooperation and established both a precedent and a standard by which future international negotiations will be measured.

SPEECH BY

SENATOR JOHN H. CHAFEE

Before The First North American Conference on Preparing for Climate Change: A Cooperative Approach
October 27, 1987

Good evening and thank you for this award. It is a real honor to be here with so many friends who understand the need to look at the big picture.

The achievements for which you are honoring me are the achievements of many people working long hours behind the scenes. Slowly but surely the public is beginning to understand the challenges we face when we talk about the greenhouse effect and ozone depletion.

Conferences like this three-day event help spread the word and teach people that all is <u>not</u> lost. If we work together, we should be able to figure out how to solve these problems.

Earlier today, we held another in a series of hearings on ozone depletion. We heard from a distinguished panel of scientists and reviewed the most recent evidence from Antarctica.

It was an excellent hearing but I must tell you, sitting on the Environment Committee, we hear and deal with all kinds of problems--acid rain, toxic waste, solid waste, and so on--and everytime we hold a hearing on ozone depletion or the greenhouse effect, those other problems are put in perspective and pale in comparison. As important as those other matters are, they cannot compare with the global threat that all of you are dealing with.

The ozone issue has recently been receiving a great deal of attention. First there was the Montreal agreement in mid-September, a remarkable achievement and a significant first step in our effort to protect the ozone layer. Then, in early October, there was more news from Antarctica--the subject of the hearing this morning.

Although "ozone" is in the news, we cannot afford to forget the problems of the greenhouse effect and global climate change. One project that I have been working on in this area has to do with the upcoming summit meeting between Mr. Reagan and Mr. Gorbachev.

The problems associated with the greenhouse effect present the United States and the Soviet Union with an opportunity. This is a chance for us to cooperate in a joint effort to address the enormous risks that are presented by global climate change.

The U.S.-Soviet dominance in ownership of the world's coal reserves--together we hold more than 40 percent of the world's coal--is another reason for our countries to begin to explore these concerns together.

American and Soviet specialists, such as our distinguished guest tonight, Dr. Budyko, have been working together under the bilateral agreement on the environment for several years. This work has been extremely productive, but the time has come to move from the scientific arena to the political arena.

It is time to initiate discussions at the highest levels between our two countries. Such activity would be a valuable, concrete product of the summit that would be recognized throughout the world as an example of sensible, mutually beneficial cooperation.

The next step will be to bring other countries into the process. To do this, the international process that led to the Montreal agreement can and should serve as a model.

Recognizing that several years of work and negotiations preceded the Montreal agreement, several of my colleagues and I are writing, and preparing to introduce in the Senate, a Resolution calling for an international convention on the global climate change issue.

Such a convention could establish the framework for an agreement to control greenhouse gases much like the Vienna Convention to Protect the Ozone Layer and the Montreal agreement to control ozone depleting chemicals.

We need to do three things to move us closer to an international agreement on controlling greenhouse gases. First, we need to foster cooperation among all nations to develop more extensive, coordinated research.

Second, we need to identify existing and potential strategies, including technologies and lifestyle adjustments, that can stabilize global climate and atmospheric concentrations of greenhouse gases at current levels.

Finally, we need to increase the worldwide dissemination of information on the causes of the greenhouse effect, its environmental and health consequences, and methods to alleviate or avoid the greenhouse effect and its consequences.

Obviously, the ozone agreement is a good model only if it is an <u>effective</u> agreement. In the sessions leading up to Montreal, all of the parties understood that the Antarctic "hole" was <u>not</u> the basis for the agreement.

In fact, Dr. Tolba, the Executive Director of the U.N. Environment Program, a prime mover behind the agreement, made an explicit pledge to call an emergency session to reopen the agreement if it turns out that the "hole" is caused by CFCs.

The most recent findings from Antarctica are very disturbing. I won't get into them now because I am sure you will be hearing about them all week. For now, it is sufficient to note that, even though the results are preliminary and are not 100% conclusive, they raise some serious questions about the Montreal agreement.

It is true that we cannot say for certain that the "hole" has global implications--although common sense tells us it must. Nevertheless, if for no other reason than to protect the Antarctic ecosystem, we should be moving to eliminate--not just reduce--CFCs, and all other man-made sources of chlorine, as quickly as possible.

Our scientific understanding of this phenomenon is advancing at an incredible rate. Given what we know today, it seems to me that we should be doing at least two things. First, the U.S. and all other countries should ratify the Montreal agreement as quickly as possible--it may not be perfect but it establishes a good framework for dealing with the problem.

Second, an emergency session of the parties should be called to review the most recent data. The meeting scheduled for 1990 is simply too far away.

The good news is that we are making progress. It is not all gloom and doom. These are difficult times and the problems you are gathered to discuss are among the most complicated and frustrating of them all. But they are also without question the most important.

Our children and our children's children are counting on us. I am convinced that we are going to rise to the challenge and look forward to working with all of you. Good luck with your conference and, again, thank you.

The Greenhouse Effect:
What We Can or Should Do About It

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THE GREENHOUSE EFFECT:
WHAT WE CAN OR SHOULD DO ABOUT IT

Palm trees in New York City?
A new dust bowl from industrial pollution and deforestation?
Newly fertile lands opening up in the USSR and Canada?
Faster growing crops?
Sea levels rising and coastlines flooded?
A hole in the ozone layer and big increases in skin cancer?
Acid rain killing our lakes?
Acid control strategies disputed as costly and ineffective?
Scientists unable to agree on details of future climate change!

No doubt, most of us have come across similar frightening, contradictory, or extravagant claims about how our climate is changing, how our own economic activities might be behind that change, and what we should--or shouldn't--do to stop--or welcome--it. Indeed, I have seen forecasts in recent media warnings of the advent of the next Ice Age, a super greenhouse effect with tropical conditions in New York, a hole in the ozone so severe that it will disrupt much of life on Earth, and a statement from a former U.S. budget director to the effect that an acid rain control program on Midwest smoke stacks would cost some six to ten thousand dollars <u>per pound</u> of fish saved in the Adirondacks. The media are increasingly carrying stories of potential or impending climatic change, including contradictory claims from academic, environmental, governmental, and industrial "experts". But, how is the public to understand first what might be happening, second what it might mean for humans and the natural environment, third what might be done about it and, fourth, how much it might cost and to whom? Cutting through all the complex arguments, although a daunting task for most professionals, let alone lay people, is nonetheless what our democracy requires: reasonably informed knowledge of the likelihood and possible consequences of our own activities so that we can send signals to our political leadership on how to act -- despite uncertainties. Unfortunately, one isn't going to learn enough about all of this from a ninety second story on the evening news, nor will occasionally wire service pieces in the local daily inform us sufficiently about critical issues with imbedded technical components. Thus, one purpose of this article on climate and its possible policy implications is not only to provide a partial survey of the principal issues, but to give an example of how non-specialists might question experts about the scientific uncertainties and policy implications of complex problems.

Three similar atmospheric problems have been debated intensely over the past decade or so, even though two of them are quite old issues. These problems are (1) the possible reduction of stratospheric ozone, (2) the generation of acid rain, and (3) the climatic change from the greenhouse effect. Acid rain has actually been known for centuries, as sulfur belched from coal burning in London and other places created toxic smogs. However, only in the past few decades has the substantial downstream impact of acidity on forests and lakes been scientifically studied in depth. The climatic influence of the gas carbon dioxide (CO_2)--a by-product of the combustion of the fossil fuels: coal, oil, and natural gas--has been known for over a century. Yet, one can still give a congressional testimony on the greenhouse effect, and find a representative or staffer surprized to discover that widespread use of our abundant coal resources could actually have long-term, global, environmental consequences!

What these three problems have in common is quite simple: all are complex and punctuated by large uncertainties, all could be long lasting, all cross state and even national boundaries, all may be hard to reverse, all are inadvertent by-products of widely supported economic activities, and all may take investments of present resources to hedge against the prospect of large future environmental changes.

Although the reduction of stratospheric ozone is perhaps the easiest to reverse of these three problems, it is the only one to have received any substantial public policy action: that is, a temporary ban in the United States on the use of certain chlorofluorocarbon (CFC) spray can propellants in the 1970's and a recent international agreement to keep emissions constrained. And that step was taken only after divisive debate among environmental and industrial scientists, reports of the National Academy of Sciences, and the fact that economically viable substitutes for spray can propellants were already capable of being substituted for some of the banned CFCs.

Acid rain has become a subject of great controversy for trans-boundary pollution between normally friendly neighbors such as the United States and Canada, or West Germany and the Scandinavian countries. Although more clearly demonstrated scientifically in terms of cause and effect linkages than the cerlebrated ozone hole and CFCs, acid rain has nonetheless received much less direct policy action, primarily because the billions of dollars price tag associated with removing sulfur compounds from English, German, Soviet, or American smokestacks has led to a loud and angry debate about cost-benefit analyses, economic viability, and the lack of absolute scientific proof that a certain degree of sulfur removal would cause a precisely predictable response in the de-acidification of rainfall or other modes of acid deposition at the surface.

Finally, the most long lasting and potentially most irreversible and global problem is the greenhouse effect, whereby gases such as carbon dioxide, CFCs, methane (produced, eg, from rice in agriculture and by animal husbandry), and a dozen or two other minute "trace" gases in the atmosphere could well cause climatic change over the next two generations as large or larger than has been experienced by civilization. Should present trends in the production of these greenhouse gases continue beyond one hundred years, climatic change larger than that experienced in modern geologic periods could be felt, with potentially substantial alteration to natural and agricultural ecosystems, human and animal health, sea level, and the distribution of climatic resources. Yet, the greenhouse problem has received the least policy oriented attention of all three air issues. This is probably for several reasons: it is fraught with technical uncertainties; it has both perceived winners and losers; no one nation acting alone can do much to substantially slow it down; dealing with it substantively could be expensive or even alter life styles; it can't be proved to everyone's satisfaction except by "performing the experiment" on the real climatic system--with us and other living things on Earth along for the ride; and finally,the principal greenhouse gas--carbon dioxide--is an inherent by-product of the use of the one commodity that is most fundamental to the economic viability of the world: fossil fuel energy (which helps to make it clear why the greenhouse problem, while the most global issue, is also the most difficult to abate).

It is helpful to break down the greenhouse effect issue into a series of stages, each feeding in to another, and then to consider how policy questions might be addressed against the background of these more technical stages.

Scientific Issues Surrounding the "Greenhouse Effect"

We'll focus on the CO_2 greenhouse issue for the sake of simplicity, although similar series of stages applies to other atmospheric questions.

Behavioral assumptions. The very foundation of the problem is behavioral assumptions that must be made in order to project future use of fossil fuels (or deforestation, since this too can impact the amount of CO_2 in the atmosphere). The essence of this issue then is not chemistry or physics or biology, but social science. It depends upon projections of human population, the per capita consumption of fossil fuel, deforestation rates, reforestation activities, and perhaps even countermeasures to deal with the extra carbon dioxide in the air. These projections depend on issues such as the likelihood that alternative energy systems or conservation measures will be available, their price, and their social acceptability. Furthermore, trade in fuel carbon (for example, a large scale transfer from coal-rich to coal-poor nations) will depend not only on the energy requirements and the available alternatives but also on the economic health of the potential importing nations. This in turn will depend upon whether those nations have adequate capital resources to spend on energy rather than other precious strategic commodities--such as food or fertilizer as well as some other strategic commodities such as weaponry. In order to project the future we can make scenarios (such as seen on Figure 1) which show alternative CO_2 futures based on assumed rates of growth in the use of fossil fuels. Most typical projections are in the 1-2% annual growth range, implying a doubling of CO_2 in the 21st century. CO_2 concentration has already increased by some 25% this century. (Other than greenhouse gases like CFC's, methane, nitrogen oxides, etc. could, taken together, be as important as CO_2 in the future greenhouse effect, but these have complicated biogeochemical interactions; thus, we'll focus on CO_2 alone for the present).

The carbon cycle. Once we have some plausible set of scenarios for how much CO_2 will be injected into the atmosphere we then need to determine what interacting biogeochemical processes control the global distribution and stocks of the carbon. This involves uptake by green plants (since CO_2 is the basis of photosynthesis, more CO_2 in the air means faster rates of photosynthesis), changes in the amount of forested area, what is planted, and how climate change affects natural ecosystems. As a concrete example of how large natural climatic change (ice age to interglacial formations) affects natural ecosystems (the North American forests), we can look at Fig 2. This set of "snapshots" of forest status is obtained by counting forest pollen grains in lake beds and soils. During the past 15,000 years, the ice age conditions gave way to our present interglacial period of warmth. This represented some 5^{o} C global warming, with $10\text{-}20^{o}$ C warming locally near ice sheets. The boreal forests of Canada were hugging the rim of the great glacier in the U.S. Northeast some 10,000 years ago, while presently abundant hardwood species were clinging to small refuges in the South. The natural rates of forest movement that can be inferred from Fig 2 is some one km movement per year, in response to temperature changes of some 2^{o} C per thousand years. If climate were to change much more rapidly than this, then the forest would not be in equilibrium with the climate - ie, they could not keep up with the fast change and would go through a period of transient adjustment in which many hard-to-predict changes in species distribution or productivity would very likely occur. Also, since the slow removal of CO_2 from the atmosphere is largely accomplished through chemical processes in the oceans which take decades to centuries, the rates at which climate change modifies mixing processes in the ocean also need to be taken into account. There is considerable uncertainty about just how much newly-injected CO_2 will remain in the air over the next century, but most present estimates put the so-called "airborne fraction" at about 50%, which suggests that over the time frame of a century or two at least, something like half the extra CO_2 we inject will remain and be able to exacerbate the greenhouse effect.

Global Climatic Response. Once we have projected how much CO_2 (and other trace greenhouse gases) may be in the air over the next century or so, we have to estimate what its climatic meaning is. The greenhouse effect, despite all the controversy that surrounds the term, is really not at all a scientifically controversial subject. In fact, it is one of the best, most well established scientific theories in the atmospheric sciences! For example, with its very, very dense carbon dioxide atmosphere, Venus has ovenlike temperatures at its surface. Mars, with its very thin carbon dioxide atmosphere has temperatures comparable to our polar winters. The explanation of the Venus hothouse and the Martian deepfreeze is really quite clear and straight forward: the greenhouse effect. The greenhouse effect works because some gases and particles in an atmosphere preferentially allow sunlight to filter through to the surface of the planet relative to the amount of radiant energy that the atmosphere allows to escape back up through the atmosphere to space. This latter kind of energy, so-called terrestrial infra-red energy, is affected by the amount of "greenhouse" material in the atmosphere (see Fig. 3). Therefore, increase the amount of greenhouse gases, and you increase the planets' surface temperature by increasing the amount of heat that is trapped in the lowest part of the atmosphere. While that part is not controversial, what is controversial is exactly how much earth's surface temperature will rise given a certain increase in a trace greenhouse gas such as CO_2. Complications arise due to processes known as feedback mechanisms. For example, if the warming due to added CO_2 were to cause a temperature increase on Earth, the warming would likely melt some of the snow and ice that now exists. Thus, the white surface covered by the melted snow and ice would be replaced with darker blue ocean or brown soil: surface conditions which would absorb more sunlight than the previous white snow or ice. Thus, the initial warming would create a darker planet which would absorb more energy thereby creating a larger final warming. However, this is only one of a number of possible feedback mechanisms. Clouds can change in amount or brightness, for example, substantially altering the climatic response to CO_2. And because many feedback processes are interacting simultaneously in the climatic system, it is extremely difficult to estimate quantitatively how many degrees warming the climate will undergo.

Unfortunately, since there is no time over Earth history that we can turn to when the CO_2 amounts in the atmosphere were, say, twice what they are now, and at the same time look at what the Earth's climate was then, we cannot directly verify our quantitative predictions of greenhouse warming on the basis of purely historical events. Instead, we must base our estimates on natural analogs and climatic models. These are not laboratory models, since no physical experiments could remotely approach the complexity of the real world. Instead we try to simulate the present Earth climate by building mathematical models, in which the known basic physical laws are applied to the atmosphere, oceans and glaciers, and the equations that represent these laws solved in the best computers available. Then, we simply change in the computer program the effective amount of greenhouse gases, repeat our calculation, and compare it to the so-called "control" calculation for the present Earth. Many such models have been built over the past few decades and are in rough agreement that if CO_2 were to double, then the Earth's surface temperature would warm up somewhere between one and five degrees Celsius. Just for a point of comparison, the world average surface temperature difference between our present climate and the Ice Age extreme of 18,000 years ago was about five degrees Celsius colder than now. Thus, temperature change of more than a degree or two globally really is a very substantial alteration.

Regional Climatic Response. To estimate the societal importance of climatic changes, however, it is not so much global average temperature we need to study but what will be the regional distribution of evolving patterns of climatic change. Will it be drier in Iowa in 2010, too hot in India, wetter in Africa, more humid in New York, or flooded in Venice? Unfortunately, to predict the fine-scale to regional responses of variables such as temperature and rainfall requires climatic models of greater complexity and expense than are currently available. It's not that we haven't made preliminary calculations of these variables. Rather, to be honest, it would be hard to get a consensus of knowledgeable atmospheric scientists to agree that the regional predictions of state-of-the-art models are reliable. Nevertheless, there is at least some plausible suggestion that the following coherent regional features might well occur over the next fifty or so years:

wetter sub-tropical monsoonal rain belts
longer growing seasons in high latitudes
wetter springtimes in high and mid latitudes
drier mid-summer conditions (see Fig 4 in some mid latitude areas -- a potentially serious problem for the future agriculture and water supply in major grain producing nations
increased probability of extreme (see Table 1) heat waves (with possible health consequences for people and animals in already warm climates) and concomitant reduced probability of extreme cold snaps

increased sea levels by as much as a few feet over the next hundred years

It must be stressed again that considerable uncertainty remains in these predicted regional features, even though many plausible scenarios have been investigated. The principal reasons for the uncertainty are two-fold: the crude treatment in climatic models of hydrological processes and the usual neglect of the effects of the deep oceans. The latter would respond slowly -- over many decades to centuries--to climatic warming at the surface, but would also act differentially (that is, non-uniformly in space and over time). That means that the oceans, like the forests, would be out of equilibrium with the atmosphere if greenhouse gases increase as rapidly as typically projected and if climatic warming were to occur as fast as a few degrees over a century time scale. This, recall, is <u>ten times faster than the natural average rate of change</u> of temperature seen from the end of the last ice age to the present time. Furthermore, if the oceans are out of equilibrium with the atmosphere, then it will be hard to assign much credibility to specific regional forecasts like that of Fig 4 until fully coupled atmosphere/ocean models are tested and applied. This is a formidable scientifc and computational task.

<u>Environmental Impact of CO_2 Scenarios</u>. Given a set of scenarios for regional climatic change we must next estimate the impacts on the environment and society. Most important are the direct effects on crop yields and water supplies. Also of concern is the potential for altering the range or numbers of pests that affect plants, or diseases that threaten animals or human health. Also of interest are the effects on unmanaged ecosystems. For example, there is major concern among ecologists that the destruction rate of tropical forests due to human expansion is eroding the genetic diversity of the planet. That is, since the tropical forests are in a sense major libraries for the bulk of living genetic materials on Earth, the world is losing some of its irreplaceable biological resources through overdevelopment. The connection of this already formidable environmental problem to climatic change becomes clear when one recognizes that substantial future changes to tropical rainfall have been suggested by climatic models, which means that presently set aside reserves (or refugia) designed as compromise solutions to preserve genetic resources into the future may not be as effective as presently planned if rapidly evolving climatic change will cause conditions in these refugia sufficiently different from the present.

Simply, they may not sustain even those species that they are designed to protect.

Economic, Social, and Political Impacts. The estimation of the distribution of economic winners and losers, given a scenario of climatic change, involves more than simply looking at the total dollars lost and gained--were it possible somehow to make such a calculation credibly! It also requires looking at these important equity questions: "who wins and who loses?" and "how the might the losers be compensated and the winners taxed?" For example, if the cornbelt in the United States were to "move" north by several hundred kilometers from a warming, then a billion dollars a year lost in Iowa farms could well eventually become Minnesota's billion dollar gain. Although some macro-economists viewing this hypothetical problem from the perspective of the United States as a whole might see no net losses here, considerable social consternation would be generated by such a shift in climatic resources, particularly since the cause was economic activities (ie, CO_2 producing) that directed differential costs and benefits to various groups. Moreover, even the perception that the economic activities of one nation could create climatic changes that would be detrimental to another has the potential for disrupting international relations--as is already occurring in the acid rain case. In essence, what greenhouse gas-induced environmental changes create is an issue I like to call the problem of "redistributive justice."

Policy Responses

The last stage in dealing with the greenhouse effect--or other atmospheric and even some non-atmospheric problems--concerns the question of appropriate policy responses. Three classes of actions could be considered. First, is mitigation: purposeful interventions in the environment to minimize the potential effects (for example, deliberately spreading dust in the stratosphere to reflect the sunlight to cool the climate as a counter-measure to the inadvertent CO_2 warming). This solution suffers from the immediate and obvious flaw that if there is admitted uncertainty associated with predicting the inadvertent consequences of human activities, then likewise substantial uncertainty surrounds any deliberate climatic modification. Thus, it is quite possible that the inadvertent change might be overestimated by our computer models and the advertent change underestimated, in which case our intervention would be "cure worse than the disease." The prospect for international tensions resulting from such deliberate environmental modifications is so staggering, and our legal instruments to deal with this so immature, that it is hard to imagine acceptance of any substantial mitigation strategies for the foreseeable future.

The second kind of policy action, one that tends to be favored by most economists, is simply adaptation. Adaptive strategies simply say let society adjust to environmental changes without attempting to mitigate or prevent the changes in advance. We could adapt to climate change for example, by planting alternative crop strains that would be more widely adapted to a whole range of plausible climatic futures. Of course, if we don't know what is coming or we haven't developed or tested the seeds yet, we may very well suffer substantial losses during the transition to the new climate. But such adaptations are often recommended because of the uncertain nature of the redistributive character of future climatic change.

Finally, the most active policy category is prevention, which could take the form of sulfur scrubbers in the case of acid rain, abandonment of the use of chlorofluorocarbons and other potential ozone-reducing gases, or a reduction in the amount of fossil fuel used around the world. The latter policies, often advocated by environmentalists, are controversial because they involve, in some cases, substantial immediate investments as a hedge against large future environmental change, change which honestly must be admitted cannot be precisely predicted. The sorts of preventive policies that can be considered are increasing the efficiency of energy end use (in a word, conservation), the development of alternative energy systems that are not fossil fuel based, or, in the most far-reaching proposal I've seen: a "law of the air". This was proposed in 1976 by anthropologist Margaret Mead and climatologist William Kellogg. They suggest that various nations would be assigned polluting rights to keep CO_2 emissions below some agreed global standard.

In summary then, it is safe to conclude that a strong consensus of knowledgeable atmospheric scientists agrees that reduction of stratospheric ozone, increases in the deposition of acids on Earth and a warming of the climate through the greenhouse effect are highly plausible future conditions.

The consensus would hold that very rapid climatic changes will cause both ecological and physical systems to go out of equilibrium -- a transient condition that makes detailed predictions tenuous. The consensus begins to crumble over detailed assessments of the timing and distribution of potential effects, and thoroughly falls apart over the question of whether present information is sufficient to generate a societal response stronger than more scientific research on the problems-- self-serving advice which we scientists, myself included, somehow always manage to recommend.

What the public needs, of course, is not to be paralyzed by uncertainty and continuing debate among scientists, but to know what questions to ask experts. Here is my recommended list: (1) what can happen? (2) what are the probabilities of alternative outcomes you foresee? (3) how did you determine these odds? (4) what are the consequences should those outcomes occur? (5) what possible actions could mitigate those consequences or help us to adapt better or even to prevent them? (6) how much will it cost if we take various actions--or we don't? and (7), who might it cost if we take various actions--or we don't? These kinds of questions are generic to any complex technical problem with environmental, social, and political implications.

Clearly, society does not have the resources to hedge against all possible negative future outcomes. Is there, then, some simple principle that can help us choose which problems to spend our resources on? One guideline is called the "tie-in strategy". Quite simply, let us take those actions which provide widely agreed societal benefits even if the predicted change did not materialize. For instance, one of the principal ways to slow down the rate at which the greenhouse effect will be enhanced is to invest in the efficient use of energy. Conservation therefore would reduce the rate of disequilibrium among physical, biological, and social systems and could buy us time both to study the seriousness of the greenhouse effect further and ensure an easier adaptation. However, supposing it turned out that the greenhouse effects now believed to occur prove to be substantial overestimates. What would be wasted by an energy conservation strategy? First of all, it usually makes good economic sense to conserve energy (although the rate of investment in conservation does depend, of course, on other competing uses of those financial resources). However, it is certain that reduced emissions of fossil fuels -- especially coal -- will reduce acid rain, negative health effects in crowded areas from air pollution, dependence on foreign sources of fuel -- especially oil -- and so forth. In other words, climatic change is just another reason to consider a policy of strategic energy efficiency. This "tie-in" strategy therefore suggests a possible priority for policy responses to the advent or prospect of the greenhouse effect which would have societal benefits even if present estimates turn out to be exaggerations. And if, in the equally likely event, present estimates are too small, then the conservation strategy will have certainly slowed down the rate of buildup of greenhouse gases, and slowing down is critical to minimizing transient effects.

Development of alternative energy technologies is another example of a "tie-in" strategy, as is the development of alternative crop strains, trading agreements with nations for food or other climatically dependent strategic commodities and so forth. However, there would be in some circles ideological opposition to such strategies on the grounds that these activities should be pursued by individual investment decisions through a market economy not by collective action using tax dollars. In rebuttal, it can be pointed out that exactly this kind of strategic investment is made on non-economic criteria even by the most conservative people: investments in military security. It is not an economic calculus which dictates investments in a military, but rather a strategic consciousness. I am simply arguing that that strategic consciousness needs to be extended to other potential threats to our security, including a substantially altered environment occurring at unprecedented rates.

Investment to hedge against potential environmental change can, however, deny resources to other socially worthy goals. And, it is often said, won't ten more years of research provide us with the answers? Of course, more research will certainly put policy making on a firmer scientific basis, but it is my opinion that credible details about specific "winners and losers" really will not be available much before we have committed ourselves to large atmospheric changes. If we choose to wait for more certainty before preventive actions are initiated, then this is done at the risk of having to adapt to a larger, faster occurring dose of greenhouse gases, acid rain, and ozone depletion than if actions were initiated today.

And how much uncertainty is enough to prevent policy action based upon a tentative climate model? The dilemma rests, metaphorically, in our need to gaze into a very dirty crystal ball; but the tough judgment to be made is precisely how long to clean the glass before acting on what we think we see inside.

IF ONLY TEMPERATURE GOES UP BY 3°F, THEN ODDS FOR JULY HEAT WAVES* GO UP:

	ODDS NOW	ODDS IF +3°F
WASHINGTON D.C. (95°F)	17%	47%
DES MOINES (95°F)	6%	21%
DALLAS (100°F)	38%	68%

Source: Mearns, L. O., R. W. Katz, and S. H. Schneider, 1984: Changes in the probabilities of extreme high temperature events with changes in global mean temperature, J. Clim and Applied Meteorl. 23, 1601-1613.

* "Heat wave" means 5 or more days in a row with max temp above 95/100°F. threshold

Table 1.

Figure Captions

Fig. 1. Various CO_2 scenarios based on specified sets of energy growth assumptions (Lovins et al., Least-Cost Energy: Solving the CO_2 Problem, Brick House, Andover, 1981.)

Fig. 2. The relative fraction (in percent) of fossil pollen from various species of trees is shown on the maps. These pollen patterns can be correlated to climatic conditions. These maps show, for example, that at the end of the last Pleistocene Ice Age 11,000 years ago much of the northeastern United States was covered with spruce forests, which are found today in central Canada near Hudson Bay. (Source: Bernabo and Webb III, 1977, Quaternary Research 8:64-95.)

Fig. 3. Greenhouse effect arises because the earth's atmosphere tends to trap heat near the surface. Carbon dioxide, water vapor and other gases are relatively transparent to the visible and near-infrared wavelengths that carry most of the energy of sunlight, but they absorb more efficiently the longer, infrared wavelengths emitted by the earth. Most of this energy is radiated back downward. Hence an increase in the atmospheric concentration of greenhouse gases tends to warm the surface.

Fig. 4. CO_2-induced change in soil moisture expressed as a percentage of soil moisture obtained from the normal CO_2 experiment. (Source: Manabe and Wetherald, 1986. Science 232:626-628).

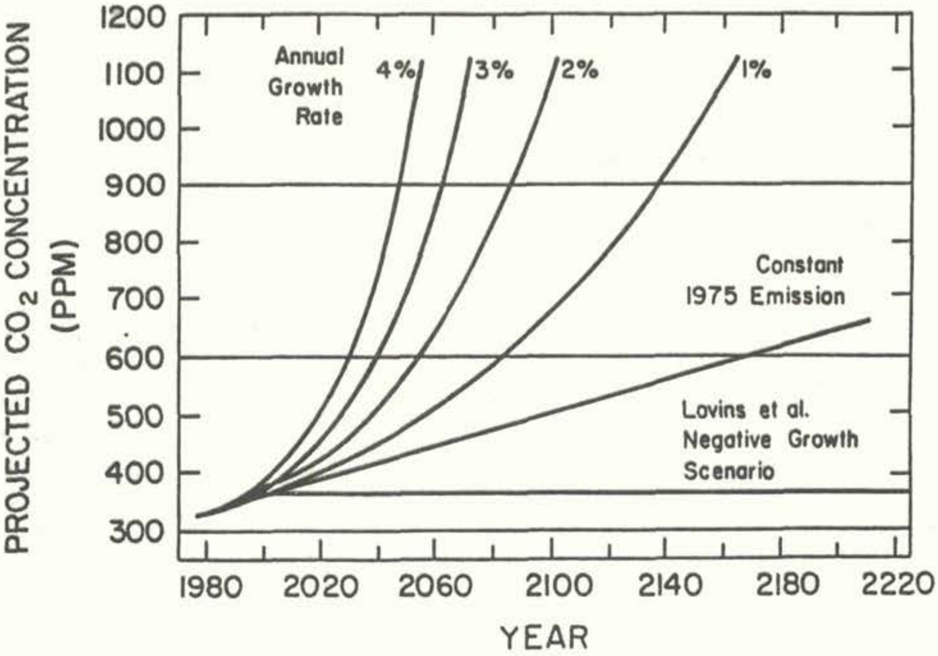

PROJECTED CO$_2$ CONCENTRATION (PPM)
1200
1100
1000
900
800
700
600
500
400
300
YEAR
1980
2020
2060
2100
2140
2180
2220
Annual Growth Rate
4%
3%
2%
1%
Constant 1975 Emission
Lovins et al. Negative Growth Scenario

Fig. 1

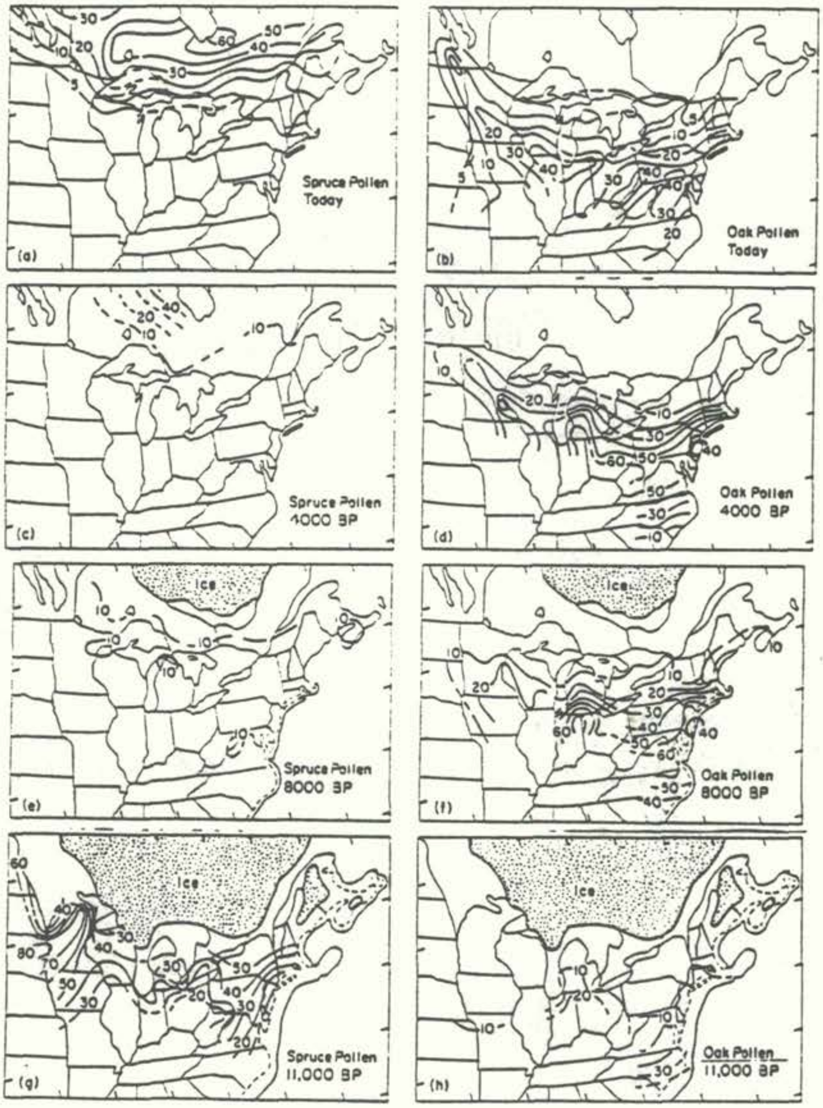
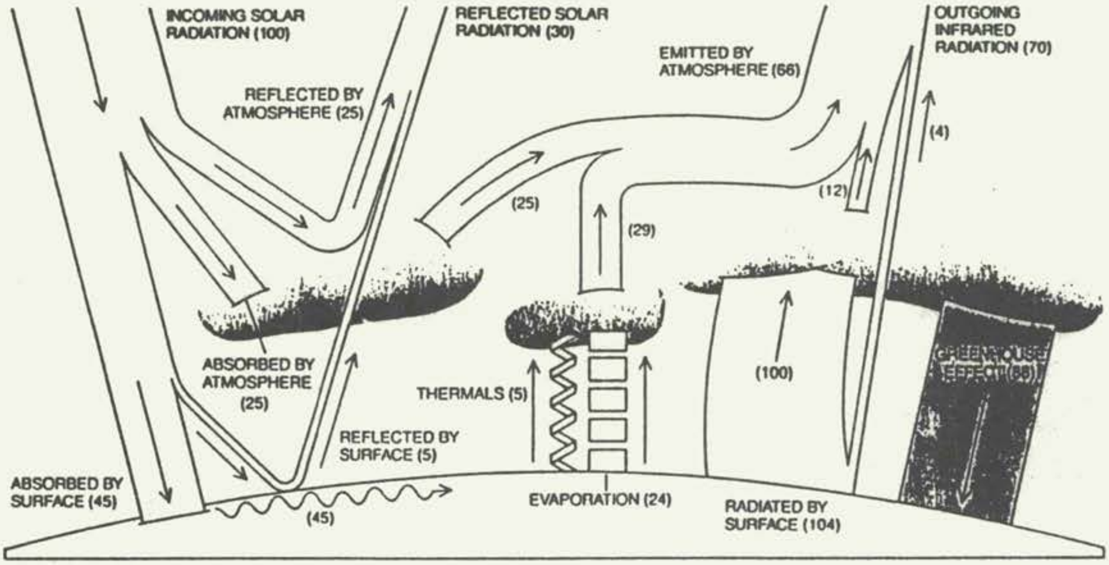
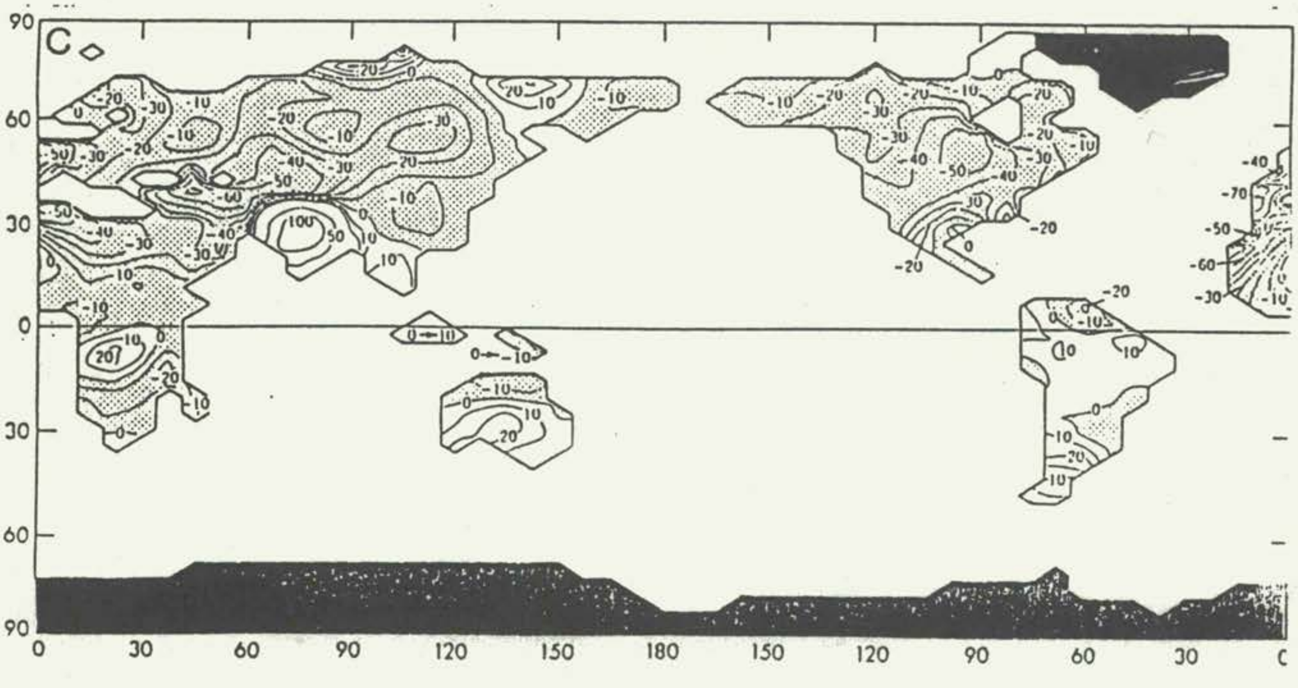

(a)
Spruce Pollen Today
(b)
Oak Pollen Today
(c)
Spruce Pollen 4000 BP
(d)
Oak Pollen 4000 BP
(e)
Spruce Pollen 8000 BP
(f)
Oak Pollen 8000 BP
(g)
Spruce Pollen 11,000 BP
(h)
Oak Pollen 11,000 BP
Ice

Fig. 2



GREENHOUSE EFFECT arises because the earth's atmosphere tends to trap heat near the surface. Carbon dioxide, water vapor and other gases are relatively transparent to the visible and near-infrared wavelengths (*blue*) that carry most of the energy of sunlight, but they absorb more efficiently the longer, infrared wavelengths (*red*) emitted by the earth. Most of this energy is radiated back downward (*dark red*). Hence an increase in the atmospheric concentration of greenhouse gases tends to warm the surface.

Fig. 3



CO_2 -induced change in soil moisture expressed as a percentage of soil moisture obtained from the normal CO_2 experiment. (Source: Manabe and Wetherald, 1986, Science 232:626-628)

Fig. 4

Prediction of Near-Term Climate Evolution: What Can We Tell Decision-Makers Now?

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This presentation is in part a review of existing scientific knowledge about the greenhouse effect and in part a description of current climate model research at the Goddard Institute for Space Studies in which we have simulated the unfolding of greenhouse climate effects during the next 10-30 years. Previous simulations of greenhouse effects have been confined to the case of doubled carbon dioxide, relevent to the middle of the 21st century; thus we must rely on the current results from the GISS model for discussion of climate trends during the near-term. The presentation was prepared for use at this conference and as testimony to the United States Senate Committee on Energy and Natural Resources on November 9, 1987. The style of presentation is aimed at a middle ground between the preference of scientists to stress all caveats in detail, and the desire of non-technical parties for an understandable practical statement of the status of scientific understanding.

1. Are Major Greenhouse Climate Changes a Certainty?

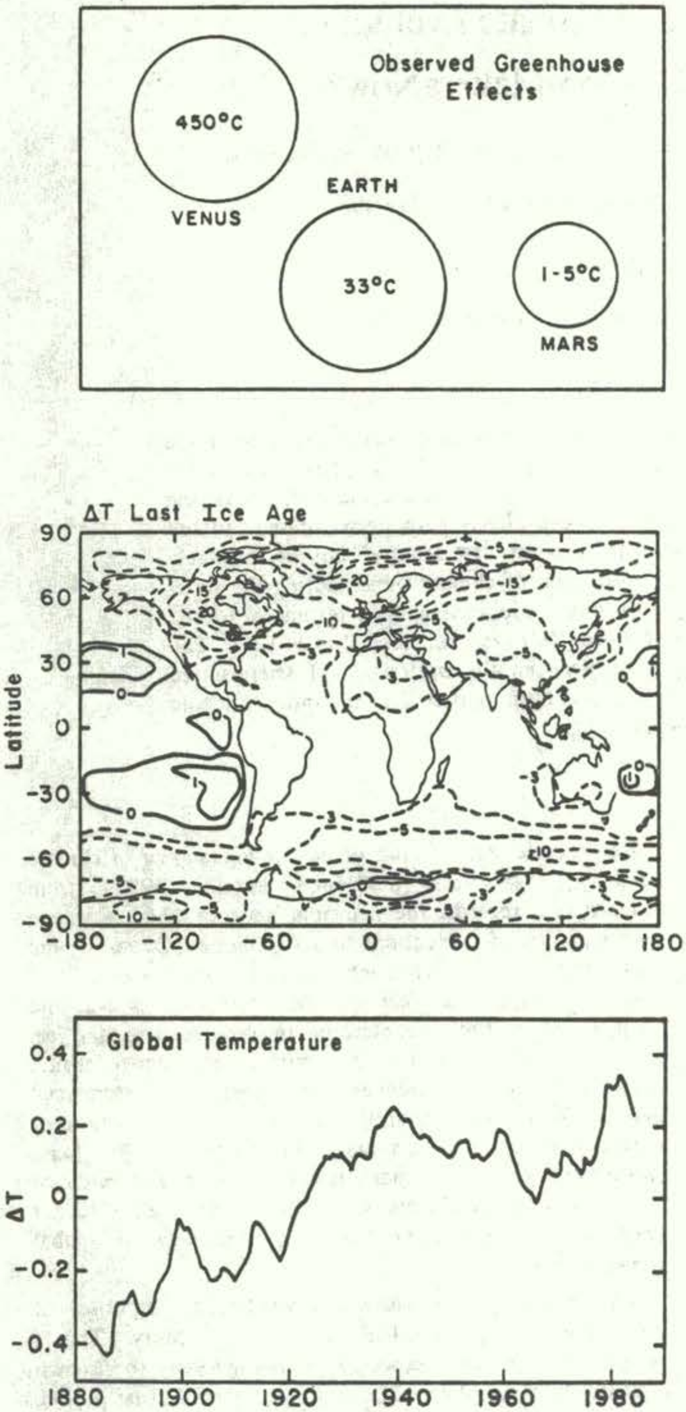
Our understanding of the greenhouse effect is based on a broad range of evidence, both theoretical and empirical. Global climate models or general circulation models (GCMs), which are mathematical representations of the atmosphere and ocean used to simulate weather and climate change on large scale computers, suggest that a doubling of atmospheric carbon dioxide will cause a global mean warming of somewhere between 2.5° and 5.5°C. Results from all the GCMs are thus consistent within about a factor of two.

Empirical evidence about climate sensitivity is more important, in my opinion, and it is consistent with the climate model results. Principal empirical evidence is summarized in Figure 1. The inner planets Venus, Earth and Mars have a broad range of greenhouse gas abundances; Venus has a very thick CO_2 atmosphere, the earth's atmosphere is of intermediate thickness, and Mars has a thin CO_2 atmosphere. These planets are each warmer than they would be without an atmosphere, given their distances from the sun. Venus has a greenhouse effect of several hundred degrees, the earth is 33°C warmer than it would be without its greenhouse gases, and Mars has a greenhouse effect of only a few degrees. The observed temperatures are consistent with the theoretical expectations for the observed atmospheric composition on each planet.

Remarkable confirmation of our understanding of climate sensitivity has been developed in the 1980's from paleoclimate records, the principal advance being accurate determination of fluctuations in atmospheric CO_2 during the past 100,000 years. Although scientists continue to debate why CO_2 changed, a great deal of information is available on how CO_2 and other climate parameters (such as land ice, sea ice cover, vegetation distribution, and earth orbital parameters) differed between ice ages and interglacial periods. This allows quantification of the contribution of different processes to a well documented large global climate change. The important result is empirical evidence for an equilibrium climate sensitivity of about 2.5°-5°C for doubled CO_2, consistent with the sensitivity of global climate models.

Additional empirical evidence is provided by the observed global warming of about 0.6°C in the past century. This is consistent with the expected warming due to known increases of atmospheric CO_2 and trace gases in that period. This empirical evidence does not provide as precise a measure of climate sensitivity as we might hope, because part of the warming due to increased greenhouse gases is delayed due to the thermal inertia of the oceans; the delay is greater if climate sensitivity is greater, so the short-term temperature rise is not so different between cases of low

EMPIRICAL BASIS OF UNDERSTANDING



OTHER PLANETS:
Venus (400°C), Earth (15°C) and Mars (-50°C) have a broad range of temperatures consistent with greenhouse gas abundances

PALEOCLIMATE RECORDS:
Glacial to interglacial climate changes were accompanied by large changes in atmospheric CO_2, which appear to have been the principal mechanism of climate change

RECENT CLIMATE TRENDS:
Global warming of 0.6°C (1°F) in the past century is consistent with the increase of atmospheric CO_2 and trace gases in that period

Fig. 1. Examples of empirical data which provide quantitative estimates of climate sensitivity.

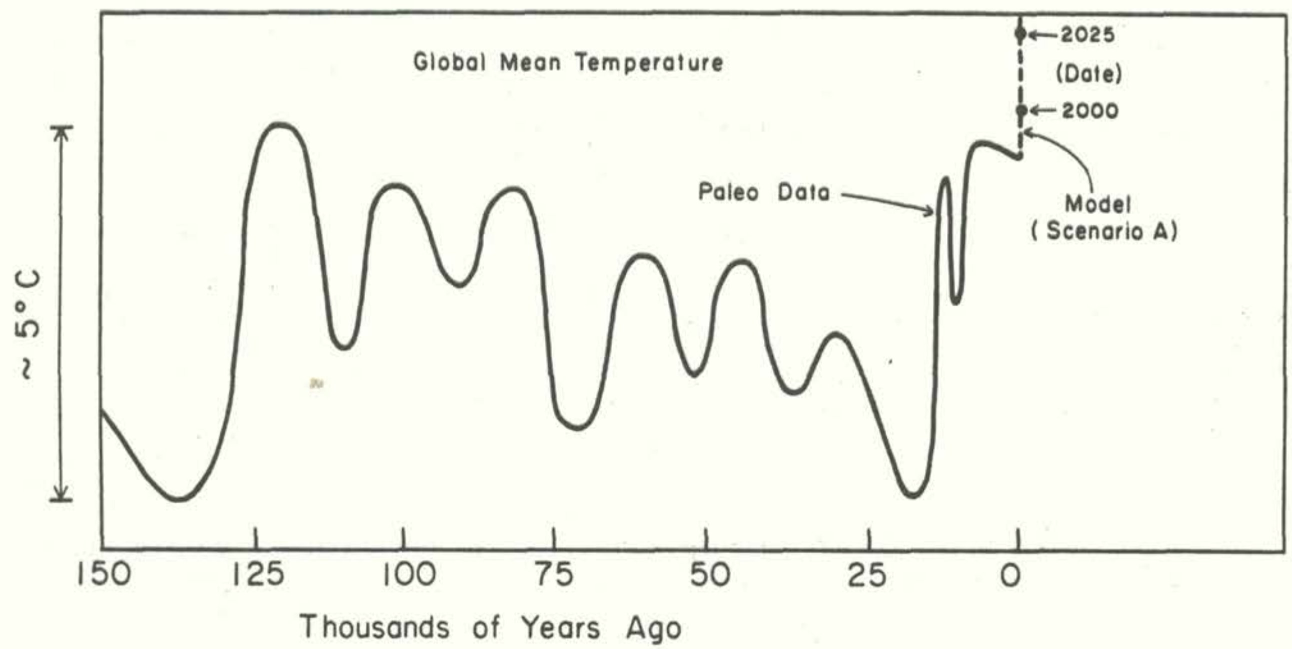


Fig. 2. Smoothed global mean temperature trend during the past 150,000 years and the simulated future temperature trend for trace gas emission scenario A.

and high climate sensitivity. This ambiguity could be removed if we measured accurately the rate of heat storage in the ocean. At this time we can only say that the observed warming in the past century is consistent with any climate sensitivity in the range 2°-5°C for doubled CO_2.

Conclusion. In view of the facts that (1) even conservative projections of CO_2 and trace gas growth indicate an equivalent doubling of CO_2 by the second half of next century, and (2) the warmest time in the past 100,000 years was only about 1°C warmer than today (cf. Figure 2), we can confidently state that major greenhouse climate changes are a certainty. However, as shown by results below for different trace gas scenarios, the impacts are much less in scenarios with reduced trace gas growth rates.

2. Can We Predict Greenhouse Changes That Will Occur in the Near-Term, Say in the next 10-30 Years

Prediction of near-term climate trends, as opposed to equilibrium doubled CO_2 climate changes, introduces several major complications. First, we must give up the luxury of using an arbitrarily fixed CO_2 change, and instead consider how CO_2 and trace gas abundances might evolve in the real world. Second, instead of solving for an equilibrium response relevant to some poorly specified far-future date, we must tackle the time-dependent response of the climate system; that means we must account for the ocean's role in climate change, since the ocean is the principal source of thermal inertia in the climate system. Third, because near-term greenhouse climate effects are small compared to those for doubled CO_2, we must be concerned about other climate forcings which may be comparable to greenhouse gases, and we must compare predicted climate changes to natural variability of the system.

Trace gas scenarios: CO_2 and other trace gas abundances are reasonably well known for the period since 1958, when CO_2 began to be monitored accurately, as illustrated in Figure 3. Although it is very difficult to predict future

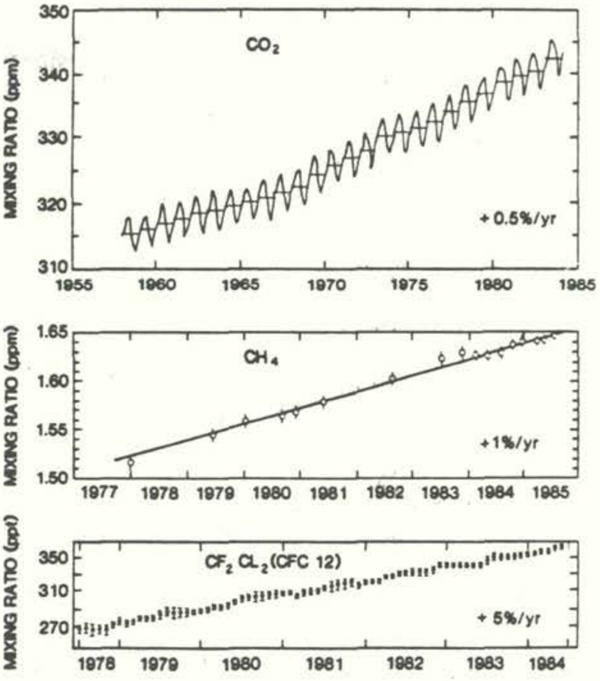


Fig. 3. Recent trends in the atmospheric abundance of three of the principal greenhouse gases in the earth's atmosphere.

trends, our objective is to consider a broad range of scenarios to help evaluate the implications of different alternatives. The three scenarios we employ (Figure 4) are:

Scenario A - continued growth of emissions at rates which are compounded annually, and thus are exponential; e.g., CO_2 emissions increase 1½%/year and CFC emissions increase 3%/year.

Scenario B - fixed annual growth of greenhouse forcing; if population grows, this scenario implies a reduction in per capita emissions.

Scenario C - greenhouse forcing ceases to increase after year 2000; CFC emissions are terminated by 2000 and other trace gas emissions just balance their sinks; this would require drastic cuts in fossil fuel use, perhaps half of the current use.

In view of resource constraints and environmental concerns, Scenario A must eventually yield unrealistically large greenhouse forcing. Scenario C, on the other hand, represents a more drastic curbing of emissions than usually has been contemplated. Scenario B is probably the most plausible of the three scenarios.

Transient ocean response: The time dependent response of the climate system to changes of climate forcing depends principally upon the ocean. Unfortunately, capabilities for modeling the global ocean are much more primitive than capabilities for modeling the atmosphere. As a result, for the climate simulations which we present here we make a gross simplifying assumption about ocean heat transports: we assume (1) that for the next few decades the pattern of horizontal heat transport by ocean currents will remain the

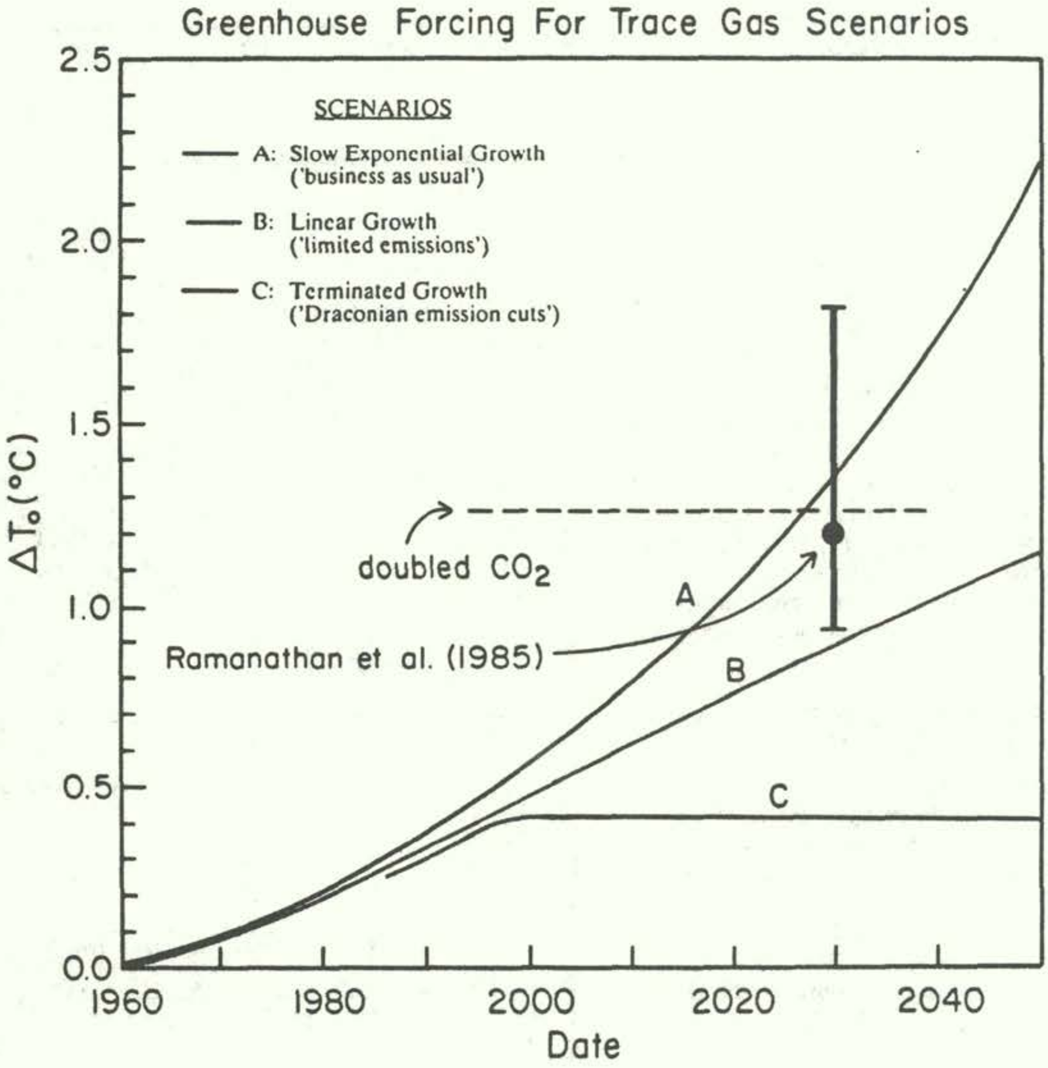


Fig. 4. Three trace gas scenarios used for simulations of future climate with the GISS GCM, as described in the text. ΔT_o is the "greenhouse forcing", specifically the equilibrium global mean warming that would occur if there were no climate feedbacks. The doubled CO_2 level of forcing, $\Delta T_o \sim 1.25°C$, occurs when the CO_2 and trace gases added after 1958 provide a forcing equivalent to doubling CO_2 from 315 ppm to 630 ppm. The CO_2 + trace gas forcing estimated by Ramanathan et al. [*J. Geophys. Res.*, *90*, 5566, 1985] for 2030 is also illustrated.

same as it is today, and (2) heat perturbations penetrate the deep ocean at a rate based on observed penetration of inert tracers (such as tritium sprinkled on the ocean in nuclear testing).

Although these assumptions are plausible for small climate perturbations, it must be recognized that we are thereby forcing the ocean to be relatively surprise-free. In the real-world, climate changes at the ocean surface may induce changes in ocean heat transports, thus leading to other, perhaps larger, climate changes. Broecker, for example, has stressed the possibility of changes in Gulf Stream and related ocean transports. Especially because of these assumptions about the ocean, it is unlikely that we can predict regional climate surprises; this is somewhat analogous to the difficulty that atmospheric chemistry models have in predicting or simulating post facto the Antarctic ozone hole.

Other climate forcings: At the present time the climate forcing due to increasing greenhouse gases is not large enough to completely dominate other global climate forcings such as changes of atmospheric aerosols or changes of solar irradiance (Figure 5). For example, the solar irradiance was observed to decrease by ~ 0.09% between 1979 and 1985, which represents a somewhat larger forcing (of the opposite sign) than the forcing due to the atmospheric CO_2 increase in the same period. An even larger global climate forcing occurred in the period 1982–1984 due to stratospheric aerosols generated by the volcano El Chichón (Figure 5, lower panel), which would tend to cause a global cooling for at least that period.

Climate forcings such as changes in solar irradiance and stratospheric aerosols increase and decrease with time, and thus eventually are overwhelmed by monotonically increasing greenhouse gases. But on the time scale of a decade or so, the climate effects of these other forcings may be noticeable and impact our ability to detect the greenhouse effect. In our climate simulations we include the climate forcing due to stratospheric aerosols; we employ available measurements of aerosol opacity for the period 1958 to the present and we examine the impact of alternative assumptions for the level of future volcanic activity. We do not include variations of solar irradiance, because measurements are only available for the past several years. It is important that these climate forcings continue to be monitored to allow interpretation of current and future climate trends.

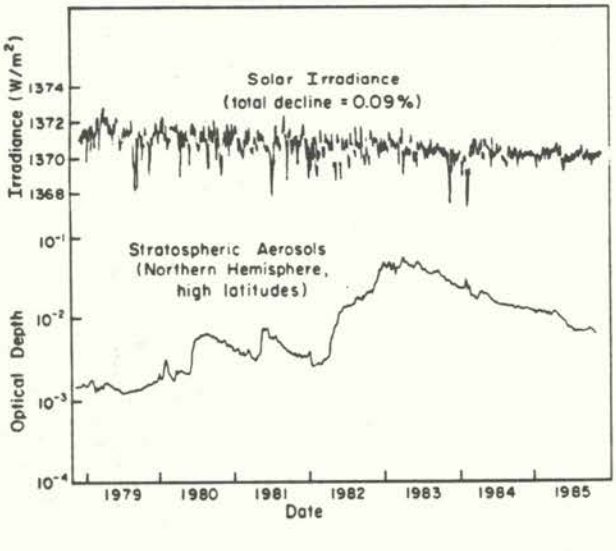


Fig. 5. Solar irradiance and optical depth of stratospheric aerosols, both as observed from the NASA Nimbus 7 satellite.

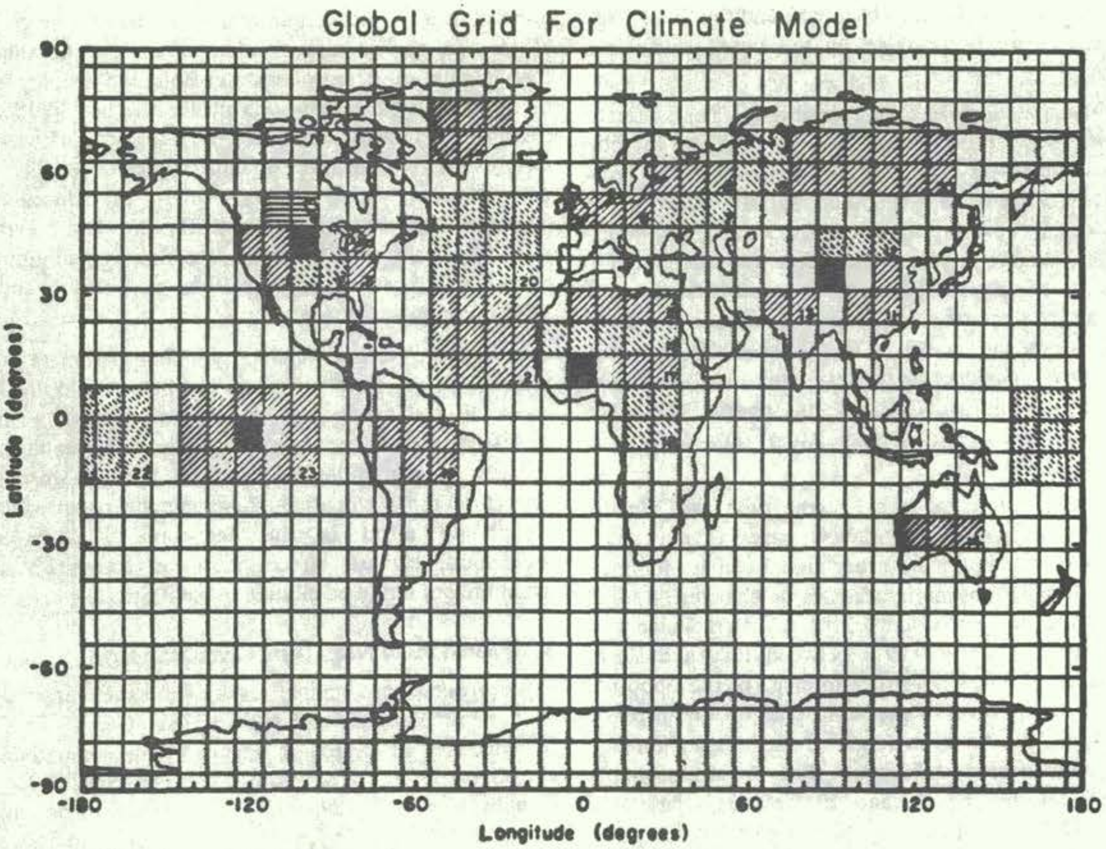
Conclusion. We can simulate greenhouse climate effects for assumed future trace gas scenarios, but, in addition to being aware of the uncertainty in climate sensitivity, which was discussed above, we must recognize the implications of simplifying assumptions about the ocean. Moreover, the impact of other climate forcings can be comparable to the greenhouse effect in the near-term. Finally, predicted greenhouse climate effects must be compared with the magnitude of unforced climate fluctuations.

3. Simulations of Near-Term Climate Change

We present here sample results from the transient climate change simulations with the GISS GCM. This GCM, schematically illustrated in Figure 6, has been documented elsewhere [*Mon. Wea. Rev.*, *111*, 609–662, 1983; AGU Geophys. Mono. *29*, 130–163, 1984]. The principal characteristics affecting the simulations reported here are:

Global sensitivity: The model has a sensitivity of about 4°C for doubled CO_2; *ocean transports*: horizontal transport by ocean currents is specified, based on estimates for today's ocean; uptake of heat perturbations by the deep ocean is mimicked as a diffusive process dependent on local stability of the water column, calibrated by measurements of transient tracers; *trace gas growth*: scenarios employed are illustrated in Figure 4; *stratospheric aerosols*: observed trends are used for the period 1958–1985, which included large volcanic injections by Mt. Agung in 1963 and El Chichón in 1982; scenario A assumes that near-term future volcanic aerosols will be negligible, as was the case in 1915-1960; scenarios B and C assume a volcanically active future, as in the period 1958-1985, by inserting large volcanoes in 1995, 2015, 2025; *other climate forcings*: no changes of solar irradiance or other climate forcings are included.

The computed global mean temperature trends for scenarios A, B and C are illustrated and compared with observations in Figure 7. Interpretation of Figure 7 requires quantification of the magnitude of natural variability, in both the model and observations, and the uncertainty in the measurements. The standard deviation of the model's global mean temperature is about 0.1°C. The standard deviation about the 100 year mean for the observed surface air temperature trend of the past century (which has a strong trend) is 0.20°C; it is 0.12°C after detrending [*Science*, *214*, 957–966, 1981]. It is not surprising that the variability of the observed global temperature exceeds the


Global Grid For Climate Model

Fundamental Equations

Conservation of momentum: (Newton's second law of motion)	$\frac{d\mathbf{V}}{dt} = -2\mathbf{\Omega} \times \mathbf{V} - \rho^{-1}\nabla p + \mathbf{g} + \mathbf{F}$	(T1)
Conservation of mass: (continuity equation)	$\frac{d\rho}{dt} = -\rho\nabla \cdot \mathbf{V} + C - D$	(T2)
Conservation of energy: (first law of thermodynamics)	$\frac{dI}{dt} = -p\frac{d\rho^{-1}}{dt} + Q$	(T3)
Ideal gas law: (approximate equation of state)	$p = \rho RT$	(T4)

Notation

$\mathbf{V}$	velocity relative to rotating earth
t	time
$\frac{d}{dt}$	total time derivative $\left[= \frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right]$
$\mathbf{\Omega}$	planet's angular rotation vector
ρ	atmospheric density
$\mathbf{g}$	apparent gravity [= true gravity $- \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r})$]
$\mathbf{r}$	position relative to planet's center
$\mathbf{F}$	force per unit mass
C	rate of creation of (gaseous) atmosphere
D	rate of destruction of atmosphere
I	internal energy per unit mass [$= c_v T$]
Q	heating rate per unit mass
R	gas content
c_v	specific heat at constant volume.

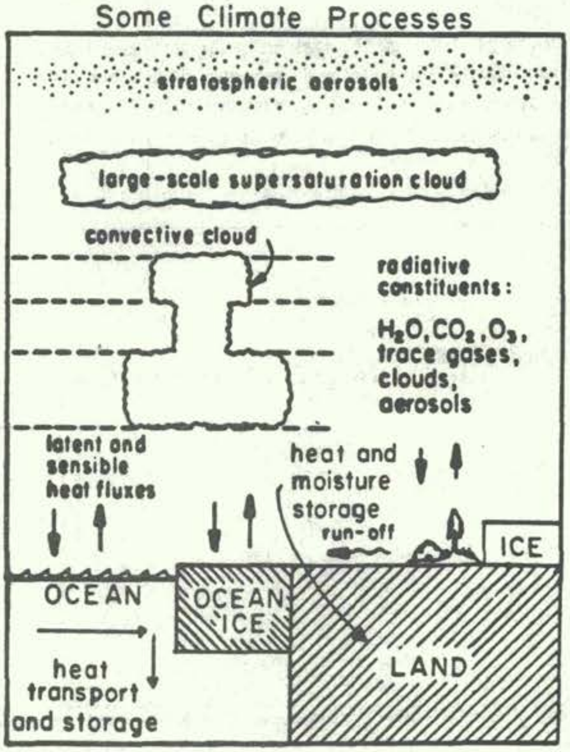

Some Climate Processes

Fig. 6. Schematic illustration of GISS global climate model.

variability in the GCM control run, since the latter contains no variable climate forcings such as changes of atmospheric composition or solar irradiance. Finally, we note that the one-sigma error in the observations due to incomplete coverage of stations is about 0.05°C for the period 1958-1985 [Hansen and Lebedeff, *J. Geophys. Res.*, *92*, 13,345-13,372, 1987], which does not contribute appreciably to the 0.12°C variability (standard deviation) of the observed global temperature. We conclude that a warming of about 0.4°C is required to be significant at the 3σ level (99% confidence level).

There is no clearly significant warming trend in either the model or observations for the period 1958-1985. During the single year 1981 the observed temperature nearly reached the 0.4°C level of warming, but by 1985 the observed temperature was no greater than in 1958.

The model predicts, however, that within the next few years the global temperature will reach and maintain a 3σ level of global warming, which is clearly significant. Although this conclusion depends upon certain assumptions, such as the climate sensitivity of the model and the absence of large volcanic eruptions in the next few years, it is robust for a very broad range of assumptions about CO_2 and trace gas trends, as illustrated in Figure 7.

Another conclusion is that global warming to the level attained at the peak of the current interglacial and the previous interglacial is inevitable; even with the drastic, and probably unrealistic, reductions of greenhouse forcings in scenario C, a warming of 0.5°C is attained within the next 15 years. The eventual warming in this scenario would exceed 1°C, based on the forcing illustrated in Figure 2 and the climate sensitivity of our GCM. The 1°C level of warming is exceeded during the next few decades in both scenarios A and B; in scenario A that level of warming is reached in less than 20 years and in scenario B it is reached within the next 25 years.

The geographical distribution of the predicted surface air temperature change for the intermediate scenario B is illustrated in the left column of Figure 8 for the 1980s, 1990s and 2010s. The right column is the ratio of this decadal temperature change to the interannual variability (standard deviation) of the local temperature in the 100 year

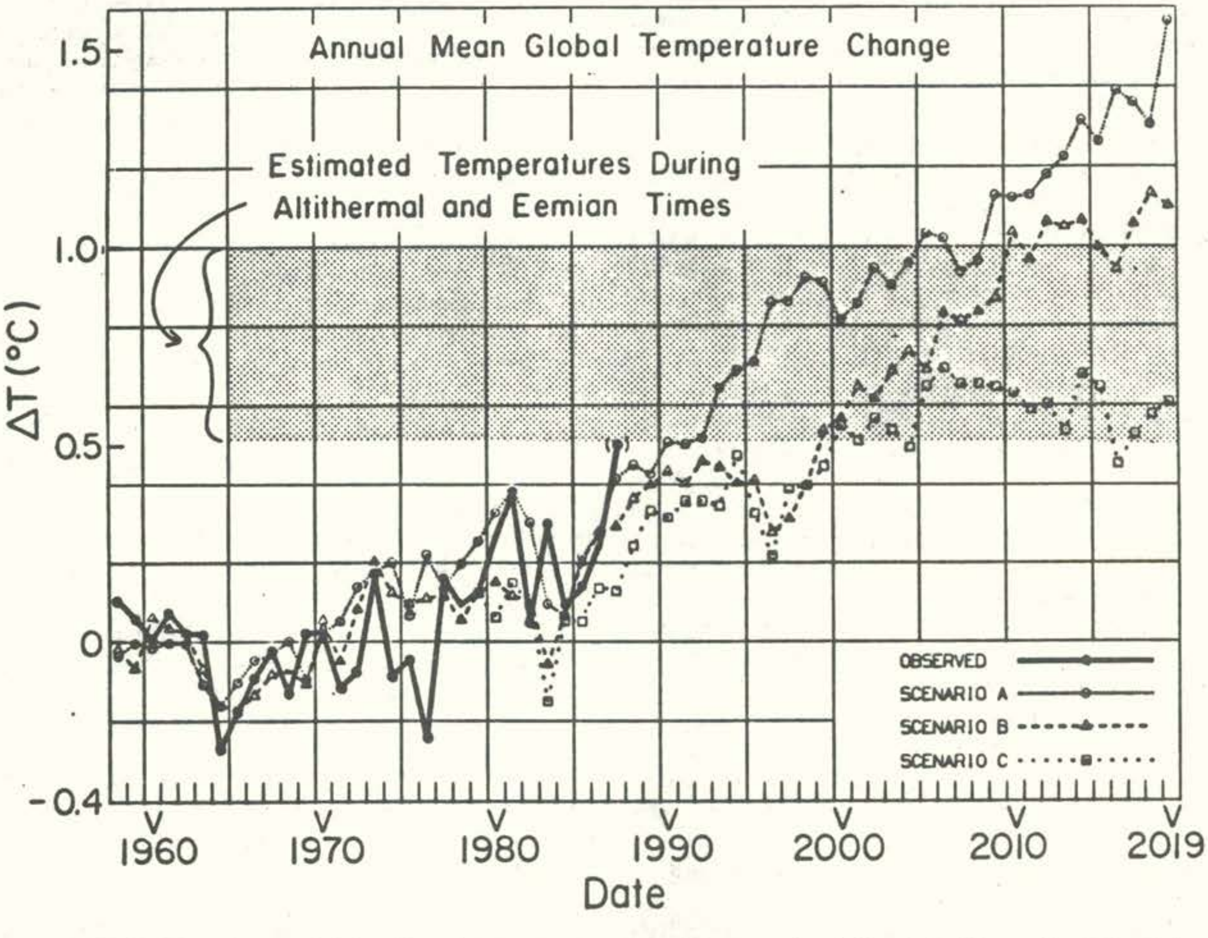


Fig. 7. Annual mean global surface air temperature computed for scenarios A, B and C. Observational data is from Hansen and Lebedeff [*J. Geophys. Res.*, *92*, 13,345, 1987]. The shaded range is an estimate of global temperature during the peak of the current and previous interglacial periods, about 6,000 and 120,000 years before present, respectively. The zero point for observations is the 1951-1980 mean; the zero point for the model is the control run mean. Observed temperature anomaly for 1987 is based on available station data for January 1 to November 1.

control run of the GCM. Since the interannual variability of surface air temperature in the model is reasonably similar to the variability in the real world, this ratio provides a practical measure of when the predicted mean greenhouse warming is locally significant.

Averaged over the full decade of the 1980s, the model indicates a tendency toward warming, but in most regions the decadal-mean warming is less than the interannual variability of the annual mean. In the 1990s the decadal-mean warming is comparable to the interannual variability for many regions, and by the 2010s essentially the entire globe has very substantial warming, as much as several times the interannual variability of the annual mean.

The man-in-the-street is more likely to notice whether the monthly mean climate is hotter or colder than normal, rather than changes of decadal mean temperature. Thus in Figure 9 we illustrate maps of computed temperature anomalies for a particular month (July) in several different years. These maps illustrate that when the temperature is averaged over a period as short as one month, there are in the 1980s about as many areas colder than normal as warmer than normal. A noticeable trend toward warming occurs within 10–15 years, illustrated by model results for 2000, but at that time there are still many areas with monthly mean temperatures colder than normal. However, after a few decades, the great majority of regions are significantly warmer than normal in any given month.

We stress that temperature maps for any given month and year represent natural fluctuations (noise) of the climate system as well as some long-term trend due to greenhouse forcing of the climate system. The natural fluctuations are an unpredictable "sloshing around" of a nonlinear fluid dynamical system. Thus the maps for a specific month and year should not be taken as a prediction of detailed temperature anomaly patterns for that particular year.

It is fair, however, to examine the maps for consistent patterns and trends which can be related to physical mechanisms. For example, the warming is generally greater over continental areas than over the ocean, and greater at high latitudes than at low latitudes. The first result is expected because the oceans respond more slowly than the continents to the greenhouse heating, as a result of the ocean's large heat capacity. The surface warming in the model is greater at high latitudes than at low latitudes, because of the greater stability of the atmosphere at high latitudes and the positive sea ice/albedo feedback there.

We also note a *tendency* for the computed warming in the 1980s and the 1990s to be relatively greater than average over the U.S. southeast and less over the western United States and parts of Europe. Changes in sea level pressure patterns associated with ocean areas which warmed relatively little may provide a mechanism for such a tendency. However, very different patterns occur in some years. Moreover, it should be remembered that ocean heat transports were fixed in our model; changes in ocean transports could greatly modify the geographical patterns of temperature change.

Conclusion. The climate model results indicate that greenhouse effects on near-term global temperature trends should be apparent within the next several years. The computed greenhouse warming remains smaller than the natural variability of regional monthly mean temperature for the next decade or two, but a tendency for more warm areas than cool areas becomes apparent in the model by the 1990s.

4. Observed Climate Trends

Estimates of surface air temperature trends are based on measurements recorded at about 2000 meteorological stations which are very unevenly distributed over the globe. The uncertainties in the inferred global temperature trend are investigated quantitatively by Hansen and Lebedeff [*J. Geophys. Res.*, *92*, 13,345-13,372, 1987]. The graphs presented here are derived from that publication, but we emphasize that our results are consistent with those of other researchers [such as *Wigley*, *Jones* and others at the University of East Anglia, and *J. Angell* of Air Resources Laboratory, National Oceanographic and Atmospheric Administration (NOAA)] for the common periods of analysis.

Observed surface air temperature anomalies for the first seven years of the 1980s are illustrated in Figure 10*a*. There is evidence of warming in the observations, and the locations of greatest warming, in Asia and at high latitudes, are not inconsistent with the model simulation (Figure 8). As indicated by Figure 8, a much more conclusive comparison of the model and observations will be possible by the 1990s.

The temperature data available for 1987 is shown in Figure 10*b*. For the available months, 1987 is a remarkably warm year, indeed the warmest in the history of recording instruments. North America is particularly warm, with some areas more than 3°C above 1951–1980 climatology, while Europe is relatively cool. Low latitudes are very warm, which undoubtedly is a result of the El Niño which has been taking place during 1987. An El Niño involves the spreading of warm surface waters over certain low latitude ocean regions which normally have upwelling cold deep water; the phenomenon occurs aperiodically at intervals of about 2–7 years and tends to result in warming of the entire tropical troposphere.

As stressed in Section 3, monthly mean temperature anomalies are of great practical importance. Observations for July 1986 and July 1987 are shown in Figure 11. Figure 11 illustrates, for example, that the Southeast U.S. was warm in July 1986 and the entire eastern seaboard of the U.S. was warm in July 1987. In both of these years there are about as many midlatitude regions which are colder than normal as there are regions warmer than normal.

One reason we have illustrated observations for specific months is that it allows a calibration of the magnitude of regional anomalies which we have recently experienced, such as the warm Julys in the Southeast and on the eastern seaboard of the United States. Since the same color scale was used for the model simulations in Figure 9, it is

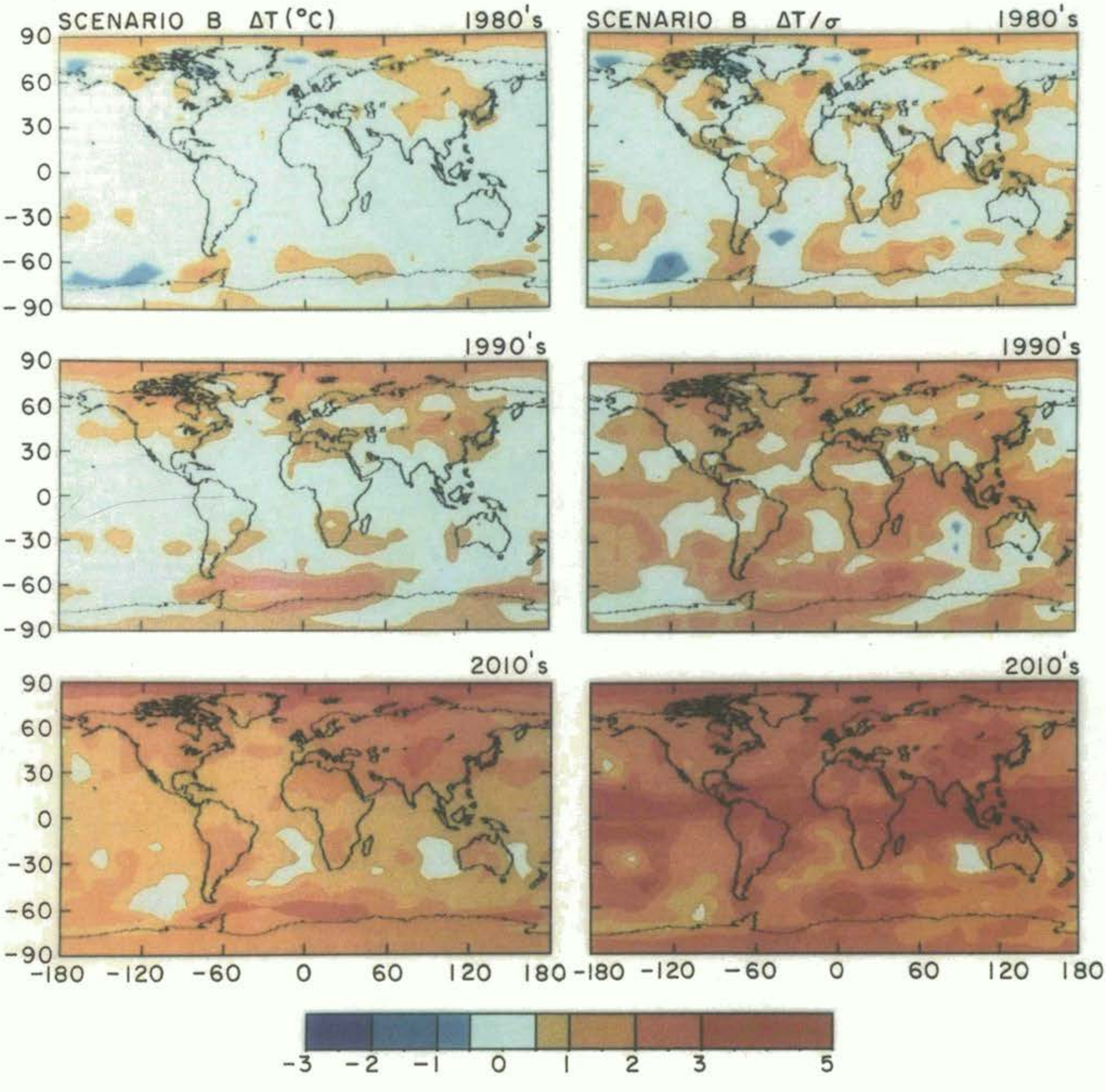


Fig. 8. Left side: decadal mean temperature change obtained for scenario B, relative to the control run, for the decades 1980s, 1990s and 2010s. Right side: ratio of the computed temperature change to the interannual variability of the annual mean temperature in the 100 year control run.

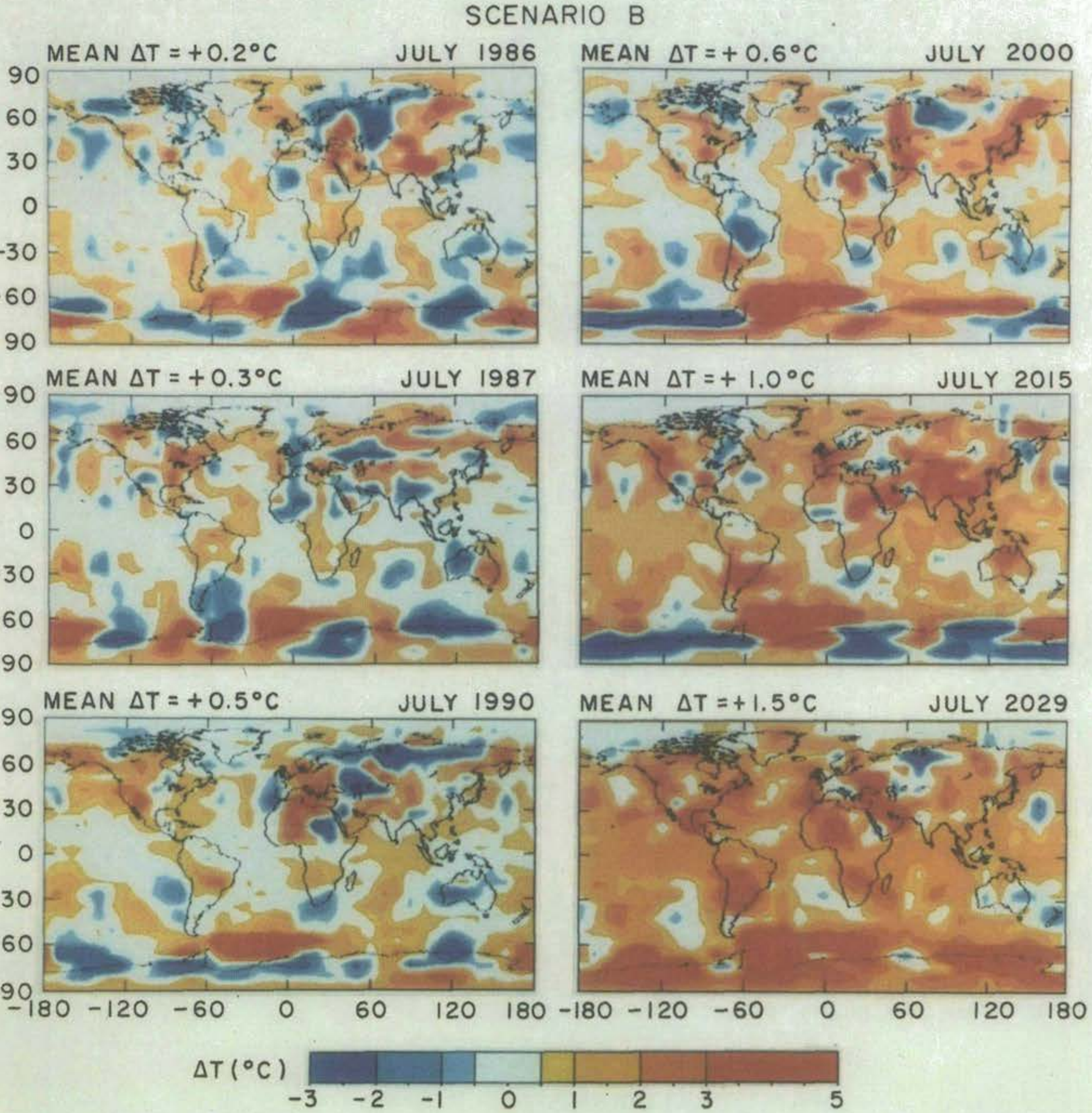


Fig. 9. Simulated July surface air temperature anomalies for six individual years, compared to 100 year control run with 1958 atmospheric composition.

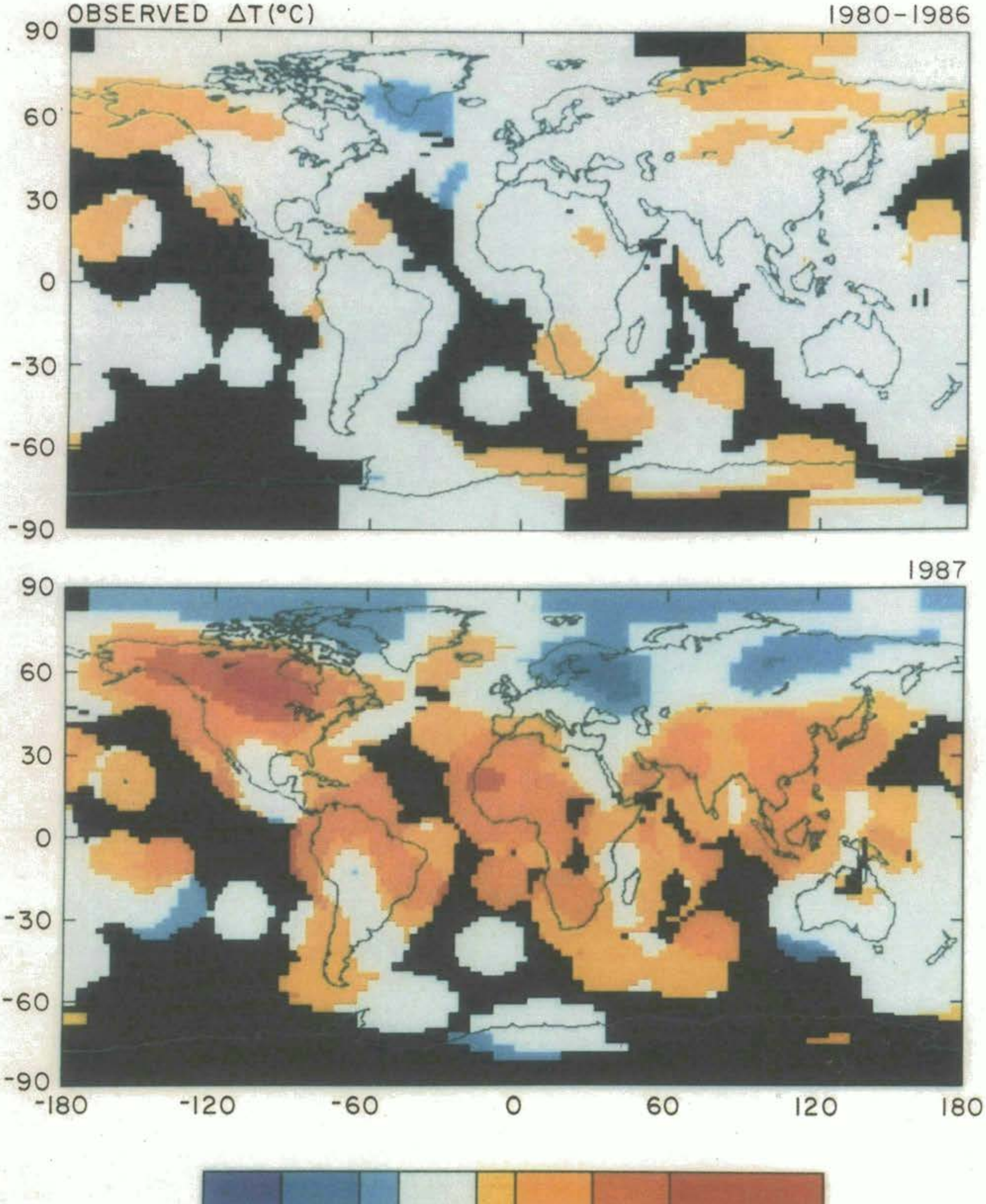


Fig. 10. Observed surface air temperature anomalies in the 1980s, relative to the 1951-1980 climatology of Hansen and Lebedeff [*J. Geophys. Res.*, *92*, 13,345, 1987]. (*a*) is the seven-year mean, 1980-1986, and (*b*) is the anomaly for 1987.

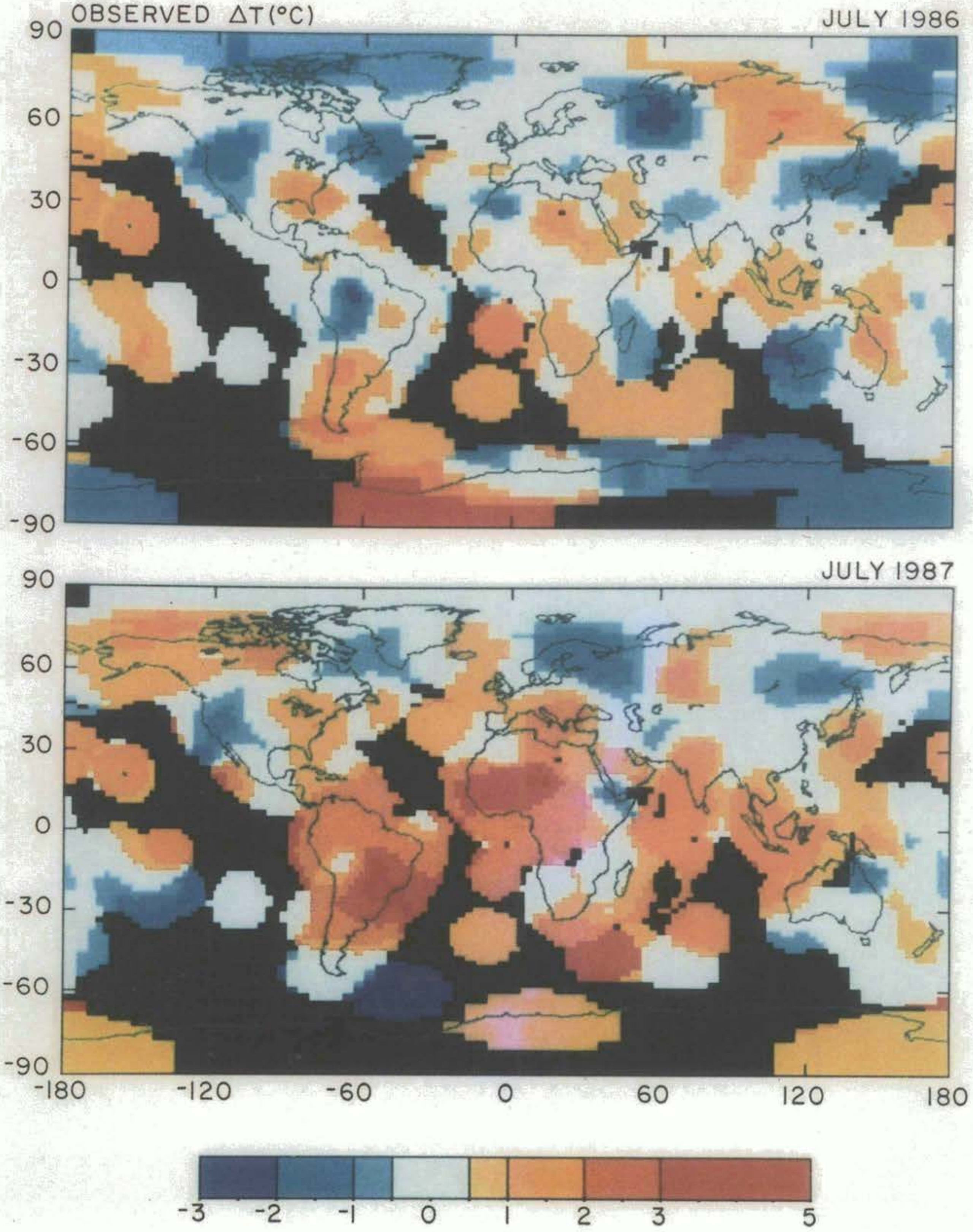


Fig. 11. Observed July surface air temperature anomalies in 1986 and 1987, relative to 1951–1980 climatology.

apparent that the model predictions for future decades represent a substantial increase in the frequency of such warm events as well as a substantial increase in the severity of the warmest events.

The global temperature trend for the past century, including the partial result for 1987, is shown in Figure 12. The earth's temperature increased by 0.5°C between the 1880's and 1960, decreased by 0.2°C between 1940 and 1965, and has increased at a rapid rate since 1965. An estimate of the rate of the current warming trend depends considerably on whether the temperature in the next few years remains near the 1987 level. Indeed, at least a temporary decrease from the 1987 level should be anticipated, in view of the probable contribution of the current El Niño to the 1987 global temperature.

Conclusion. Observations indicate a strong warming trend from the mid 1960s to the present. The global temperature in the 1980s is at the highest level in the history of recorded measurements, despite recent trends of solar irradiance and stratospheric aerosols which tend to cool the earth's surface. We conclude that there is strong evidence for an underlying warming trend, but a definitive association with the greenhouse effect requires further data and studies as described in the final section below.

5. Climate Impacts: Will the Temperature Changes Be Significant to the Man-in-the-Street

The global warming predicted to occur in the next 20 years will make the earth warmer than it has been in the past 100,000 years. It can be assumed that there will be major practical impacts of such a warming, but little research has been done to define such impacts. Indeed, warming by a few degrees may seem to be a small effect to the man-in-the-street since weather fluctuations are larger than that.

We have estimated how greenhouse warming will alter the number of days in which temperatures exceed a given threshold as a means to illustrate that warming by a few degrees (centigrade) is a large climate change. Although global climate models are not designed for local studies, we can obtain this estimate by compiling climatological data for

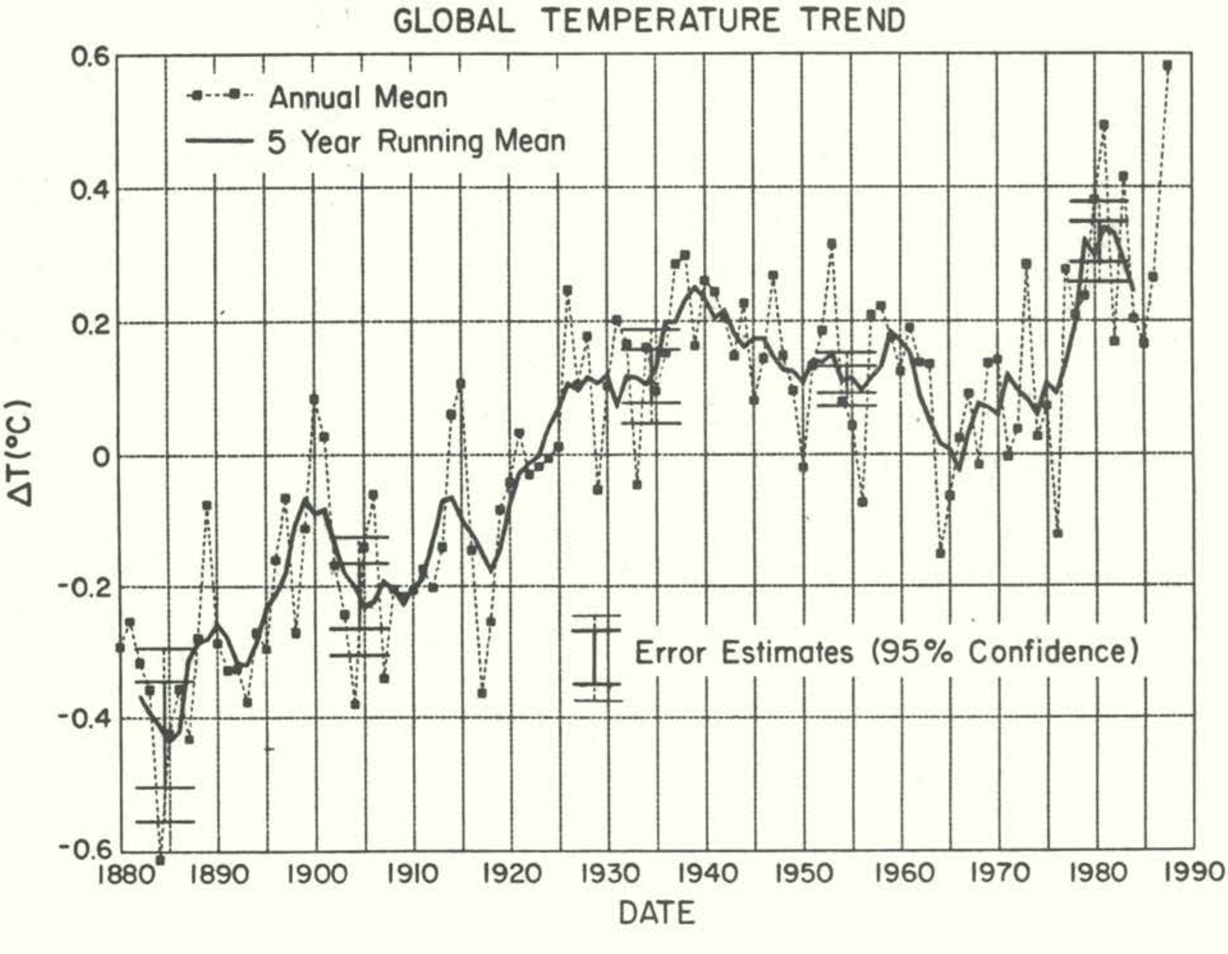


Fig. 12. Global temperature trend for the past century. The 1987 point is an estimate based on the data from January 1 to November 1.

a given city from a long series of daily observations (including maximum and minimum temperatures for each day) and adding to this record the mean (monthly) increase in daily maximum temperature and in daily minimum temperature as predicted by the climate model for the gridboxes nearest that city. This procedure tends to minimize the effects of any errors in the model's control run climatology. Although the procedure neglects changes in the higher moments of the temperature distribution, examination of our model results indicates that such changes are small.

We first carried out this procedure for the warming predicted by climate models as an equilibrium response to doubled atmospheric CO_2. This is a large climate change, some 4°-5°C in the United States, which would be applicable to the middle of next century, if the trace gas growth rate of Scenario A is approximately correct and if the climate sensitivity of current GCMs is approximately correct.

The results of this exercise for doubled CO_2 are shown in Figure 13 for several cities in the United States. The number of days per year in which the maximum daily temperature exceeds 100°F (38°C) increases from about one to 12 in Washington and from three to 20 in Omaha. The number of days with maximum temperature exceeding 90°F (32°C) increases from about 35 days to 85 days in both cities. The number of days per year in which the nighttime temperature does not fall below 80°F (27°C) increases from less than one day in both cities to about 10 days in Omaha and about 20 days in Washington, D.C. Analogous results for six other U.S. cities are included in Figure 13.

We reiterate here the principal reasons why these estimates may differ from the real world response. First, the estimates are based on a model with a sensitivity of 4°C for doubled CO_2; the real world sensitivity is uncertain within the range from about 2° to 5°C. Second, the model assumes that the ocean will continue to transport heat essentially as it does today; if North Atlantic deep water formation and the Gulf Stream should be substantially modified, for example, that could change the results for a location such as Washington, D.C. And third, there are many small-scale processes that are not resolved by the model, which could cause local responses to vary.

We make similar estimates for the number of days with temperatures exceeding 90°F for the smaller climate changes which are expected during the next few decades for our extreme trace gas scenarios A and C (Figure 14). In scenario A, profound changes in the climate would be obvious to the man-in-the-street within the first few decades of the twenty-first century. On the other hand, in scenario C the changes in decadal mean values remain smaller than the year-to-year fluctuations in the number of days with extreme temperatures. This does not imply that the climate change in scenario C is negligible, but scenario C obviously would have much smaller practical impacts than would scenario A.

Conclusion. Although there has been little quantitative research on climate impacts of greenhouse warming, it is apparent that the temperature changes predicted to result from trace gas scenarios A and B would dramatically alter the climate perceived by the man-in-the-street.

6. Climate Response Time: Implications For Emissions Policies

One aspect of the greenhouse climate problem which is particularly relevant to policy considerations is the response time of the climate system. Principally because of the great heat capacity of the oceans, the earth does not immediately respond to a change in climate forcing, but rather tends to adjust slowly over a period of years. Unfortunately, we do not yet have an accurate assessment of what the climate response time is.

The climate response time is in fact a function of climate sensitivity, as described elsewhere [*Science 229*, 857-859, 1985]. If climate sensitivity is only 1.5°-2°C for doubled CO_2, the response time may be only of the order of 10 years. But if climate sensitivity is 2.5°-5°C, as current GCMs suggest, the response time is in the range from a few decades to a century.

The implication is that a large part of the warming attributable to trace gases man has added to the atmosphere probably has not yet appeared. In addition to the warming which has occurred over the past century, we are committed to additional warming, even if increases of trace gases should be terminated immediately.

Determination of the magnitude of this unrealized warming would be greatly aided by research directed at improving our understanding of climate sensitivity. The single measurable quantity which would be most helpful in this regard is the rate at which heat is being stored in the ocean. Higher climate sensitivities (and hence greater values for the amount of unrealized warming already "in the bank") have associated with them greater rates of heat storage in the ocean. Accurate monitoring of ocean temperature along a number of ocean transects is required for this purpose. Other key measurement needs are mentioned in the next section.

Conclusion. The finite response time of the climate system implies that there is unrealized greenhouse warming already "in the bank" or "in the pipeline". This yet to be realized warming calls into question a policy of "wait and see" regarding the issue of how to deal with increasing atmospheric carbon dioxide and other trace gases.

7. What is Needed to Improve Understanding of the Greenhouse Effect and Climate Predictive Capabilities?

Scientific evidence confirming the essence of the greenhouse theory is overwhelming. The greenhouse effect is real, it is coming soon, and it will have major effects on all peoples. The greenhouse issue has not received the attention it deserves because the climate trends have not yet risen clearly above the level of natural climate variability. However, based on our model results, greenhouse effects should begin to be apparent within the

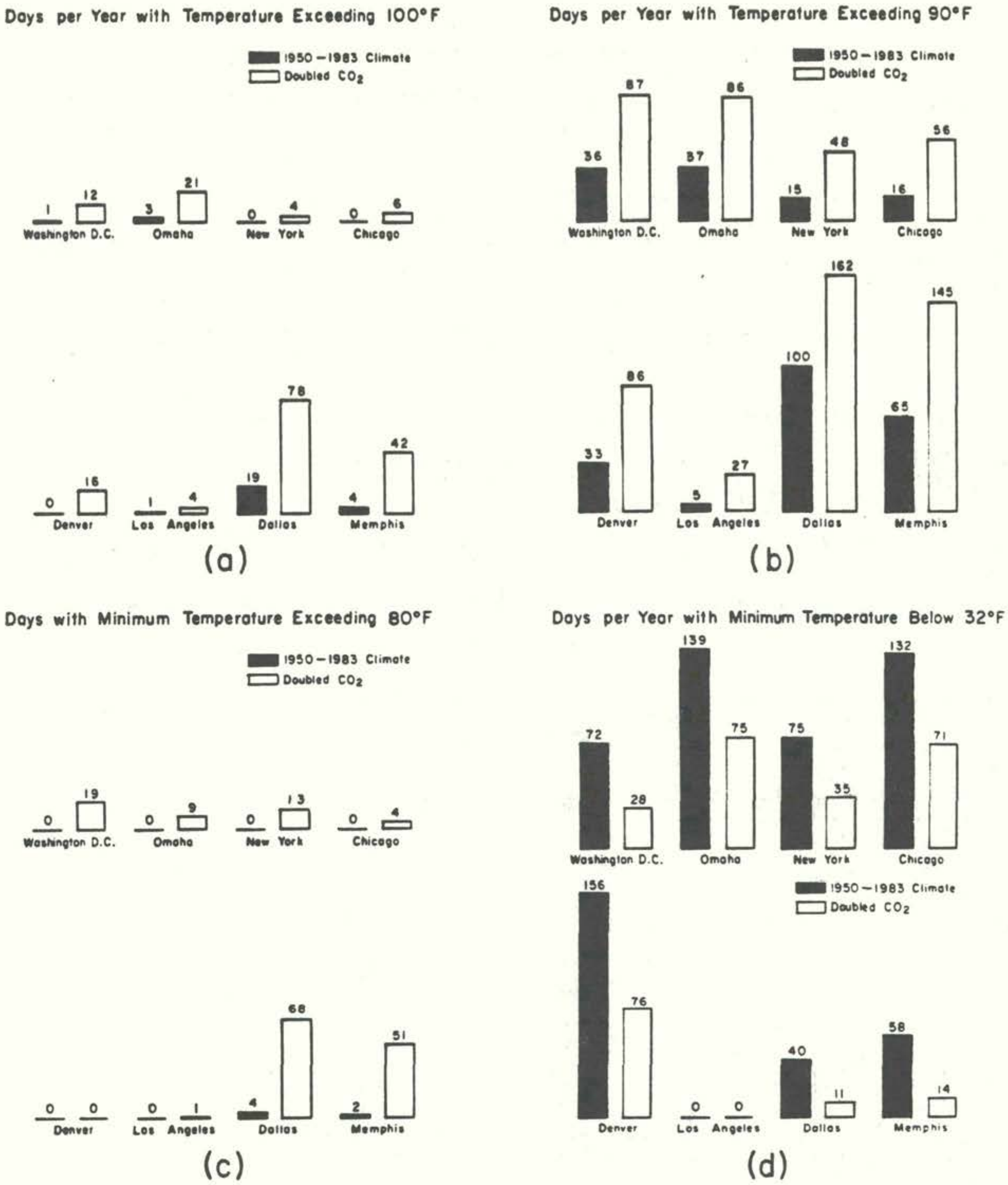


Fig. 13. Annual number of days in several U.S. cities with (*a*) maximum temperature greater than 100°F, (*b*) maximum temperature greater than 90°F, (*c*) minimum temperature greater than 80°F, and (*d*) minimum temperature below 32°F. The results for doubled CO_2 were generated by adding the warming in a doubled CO_2 climate model experiment to recorded temperatures for 1950–1983. The warming at a given city was estimated as described by Hansen et al. [in Effects of Changes in Stratospheric Ozone and Global Climate, EPA/UNEP, Washington, D.C., 379 pp., 1986]; the procedure involved interpolation from the GCM gridpoints to the city location and it included the effect of a small change in the diurnal amplitude of temperature with doubled CO_2.

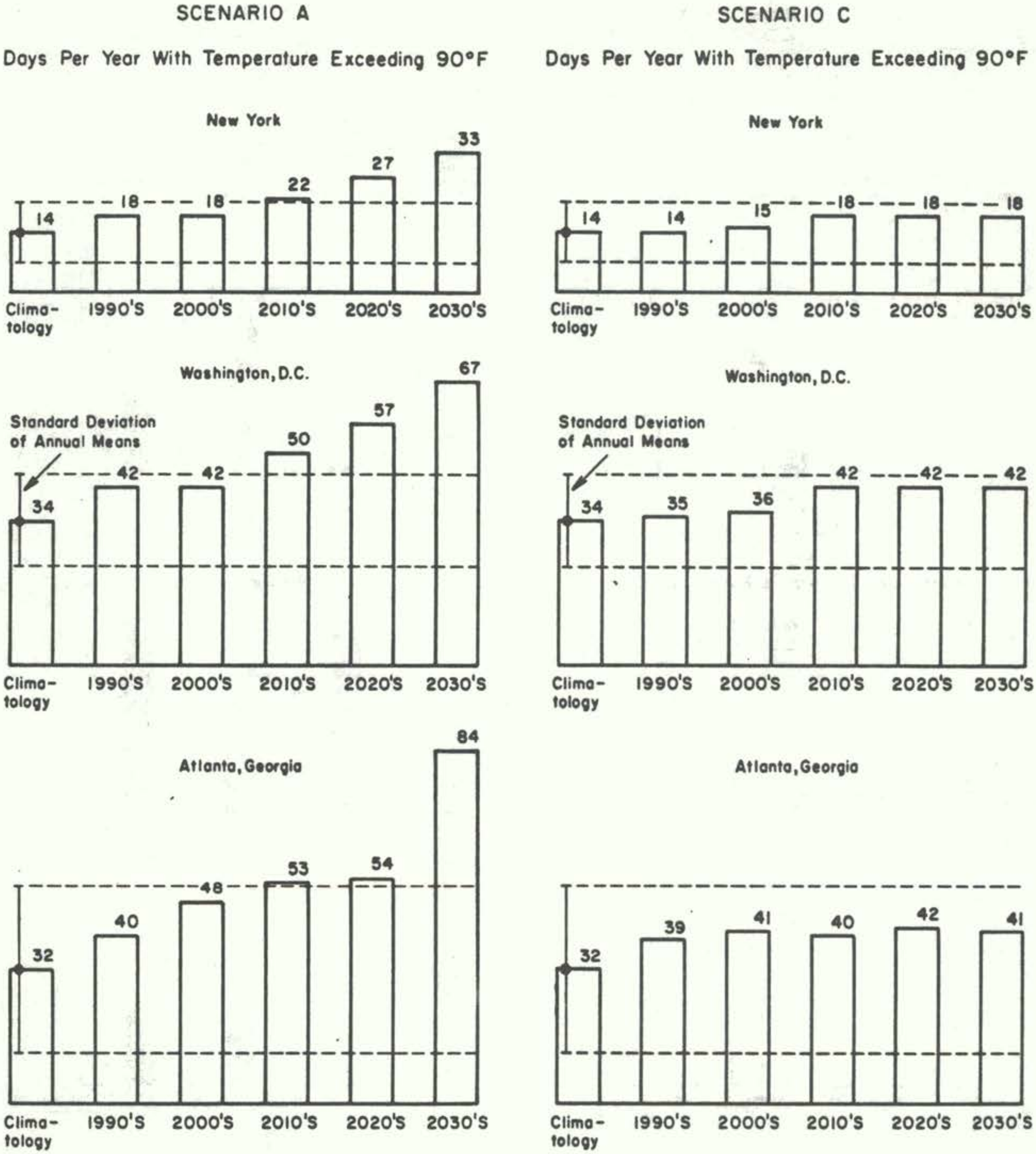


Fig. 14. Annual number of days in three U.S. cities with maximum temperature greater than 90°F. Results are shown by decade for the two extreme trace gas scenarios, A and C.

next decade.

As greenhouse climate change begins to appear, people will ask practical questions and want quantitative answers. We are now totally unprepared to provide information of the specificity that will be required. Vast improvements are needed in our understanding of the climate system and our ability to numerically simulate climate change. Key areas requiring better knowledge include the ocean circulation and heat storage, ice sheet dynamics, ground moisture and vegetation distributions, and climate feedback processes involving cloud properties, sea ice cover, the atmospheric water vapor distribution, and effects of climate change on atmospheric trace gas abundances. These research tasks will require major long-term efforts.

The greatest need, in our opinion, is for global observations of the climate system over a period of at least a decade. It is important that observational data systems be in place by the 1990s, as greenhouse effects become significant. Observations are needed to document and quantify climate trends, to allow testing and calibration of global climate models, and to permit analysis of many small-scale climate processes which must be parameterized in the global models. The data needs will require both monitoring from satellites and in situ studies of climate processes. A comprehensive discussion of required observations has been prepared by the Earth System Sciences Committee (appointed by the NASA advisory council) and is presently in press [Earth System Science: A Closer View].

Conclusion. As greenhouse climate effects inevitably grow, so will the needs for quantitative evaluation of observed climate change and reliable prediction of the consequences of alternative trace gas emission scenarios. This will require long-term global observations of the climate system accompanied by a vigorous research program.

Acknowledgement. The graphics for this presentation were produced on short notice by P. Palmer, J. Jonas and J. Mendoza. This research was supported by EPA grant R812962-01-0 and by the NASA Climate Program Office.

CANADIAN CLIMATE PROGRAM

J.A.W. McCulloch
Director General
Canadian Climate Centre

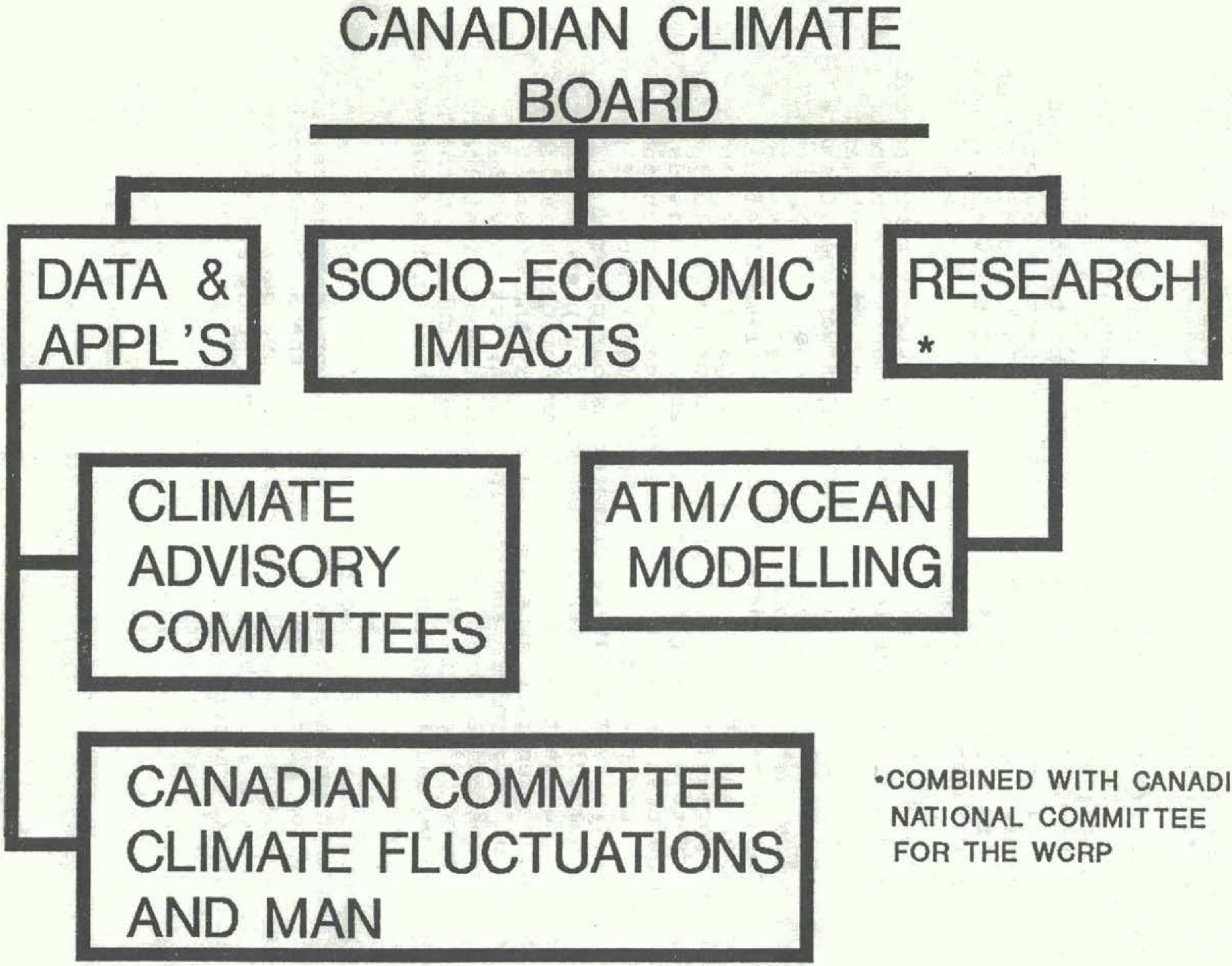
The Canadian Climate Centre is the lead agency for the Canadian Climate Program. By way of background, the Canadian Department of the Environment encompasses a variety of activities from several departments and agencies in the United States. It covers, for example, the National Parks Service, the Environmental Protection Agency, and several elements within NOAA. The Atmospheric Environment Service is one of the major elements of the Department of the Environment; its responsibilities encompass much of what is done in the National Weather Service, the Environmental Data Service, and the Environmental Research Laboratories of NOAA. The Canadian Climate Centre is one of the major elements of the Atmospheric Environment Service.

As is the case in the United States, the National Climate Program is a cooperative venture among government, universities and industry. In recognition of that, the Steering Committee, the Canadian Climate Board, has representatives from federal and provincial governments, and universities; we are indeed fortunate that this committee is chaired by Professor F. Kenneth Hare, whose name is well known to most of you in this audience. Reporting to the Board are three coordinating committees (Figure 1), again each with a broad representation from the various sectors. In particular, the Socio-economic Impacts Committee, chaired by Professor Smit who will speak to you later in this conference, advises us on what areas would be appropriate for studies into potential impacts of future global change. The Research Advisory Committee not only advises the Canadian Climate Board, but also serves as the Canadian National Committee for the World Climate Research Program. In nine of Canada's ten provinces, and in the two territories, there have been Climate Advisory Committees formed to ensure that regional interests as well as sectoral interests have a voice in the planning. The Canadian Committee on Climate Fluctuations and Man, which is chaired by Dr. Harington who will also speak to you later in the conference, deals mainly with the construction of past climates from proxy data.

We can identify the principle goals of the Canadian Climate Program as: to exploit to the maximum extent possible data now in the Climate Archive for the benefit of Canada's economic and social sectors; and, to attempt to foresee and warn of possible future variations and changes in climate, either natural or anthropogenic. In this latter activity, of course we are aligned with many countries of the world through the World Climate Research Program.

The ways in which the Canadian Climate Centre is carrying out those goals are, in parallel with the elements of the World Climate Program, through data, applications, research, and impacts. The Centre operates the Canadian National Climate Data Archive, which is based on observations made by the AES itself and a number of cooperating agencies; we expect to start adding air quality data to existing climatological information, and possibly sea ice. The staff of the Centre includes specialists in the applications of meteorology or climatology to a variety of economic sectors; the fields of water resources, agriculture, forestry, energy, urban and industrial, and the arctic are covered. The kingpin of the research activity for future climates is our general circulation model. The Centre also monitors present climate to be able to identify trends and the extent of variability. We have been preparing experimental monthly and seasonal forecasts of temperature and precipitation, but only the monthly temperature forecasts have so far shown significant skill; they will be offered to the Canadian public in the near future and we shall continue to develop skill in the other areas.

The impacts area is covered by a number of cooperative ventures with universities, other government departments, and private sector firms. Upon the advice of the Socio-economic Impacts Committee, a number of contracts have been let; the list in Table 1 shows both the area of the study and the particular contractor.



*COMBINED WITH CANADIAN NATIONAL COMMITTEE FOR THE WCRP

Figure 1: Committee Structure of the Canadian Climate Program

Table 1: Studies of Socio-economic Impacts

1. Navigation & Power Generation in the Great Lakes - University of Windsor
2. Agriculture in Ontario - University of Guelph
3. Ontario Tourism & Recreation - University of Waterloo
4. Agriculture in the Prairie Provinces - University of Manitoba
5. Agriculture in Saskatchewan - IIASA et al
6. Potential Resource & Socio-Economic Strategies in Ontario - DPA Group
7. Sea Level at Charlottetown, PEI - P. Lane Assoc.
8. Natural Resources in Quebec - University of Montreal
9. Downhill Skiing in Quebec - Lamophe & Periord, Lte
10. Marine Environment of Atlantic Canada - Dalhousie University
11. Economics - University of Toronto
12. Sea Level at St. John, N.B. - Martec Ltd
13. Forestry in the Prairies & NWT - Saskatchewan Research Council

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The list of impacts is both frightening and impressive. For example, if one puts together the result of a number of the studies applicable to the Great Lakes Region, the predictions include:

- winter ice disappears
- 20% decrease in net basin water supply
- loss of hydro-electric generating potential
- problems with water supplies for urban and other uses
- a longer shipping season, but decreased shipping capacity
- a loss of winter recreation
- lower agricultural yield
- wetlands affected, destroying a number of important natural habitats
- increased forest fire hazard and damage by forest pests.

Canada also participated in the IIASA-led study into cold margins agriculture. Five Canadians were on the team that looked at agriculture in the province of Saskatchewan, which is one of the main wheat-producing areas of the world. Included among the conclusions were more frequent and more serious drought. There would be an occasional year with drought that would cause losses to the agricultural and related economies of more than 1.5 billion Canadian dollars and eight thousand jobs. There would be an occasional decade within which the drought would lead to an annual economic loss of about 500 hundred million Canadian dollars and twenty-six hundred jobs.

Coastal regions are also expected to feel the brunt of climate change, largely due to rises in the sea level and changes in the ocean climate. For urban areas along coast lines, there would be increased danger of flooding and other water damage of neighborhoods near the water. This would be accompanied by disruption of sewage and water systems. Coastal wetlands and estuaries which are so important to the biological ecosystems of the oceans, would be seriously affected. One also expects serious disruption in the existing fishery and related industries.

While the Canadian Climate Program is much smaller than that within the United States, I feel that it is a credible and an active one. The main areas of expansion over the past several years have been in the general circulation modelling and in the socio-economic impact studies. We are finding our activities are becoming closer, indeed tending to merge, with those related to questions of air quality. It seems to make sense to work in the direction of a number of observatories each taking measurements of as many of the chemicals which are altering the atmosphere as is possible. This monitoring of atmospheric chemistry will become as much a part of the program as is the monitoring of weather and climate.

Biotic Implications of Climatic Change: Look to Forests and Soils

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Abstract

The global warming that appears now to be underway due to the accumulation of infra-red absorptive gasses in the atmosphere has the potential for destroying forests over large areas in the middle and high latitudes. The warming is open ended: no obvious mechanism exists to deflect or limit it. The speed of the warming, widely thought to be in the range of 0.5 - 1.0 degrees or more per decade, exceeds any known previous climatic change and will have effects on the earth and on the human circumstance that are well beyond the limits of experience of scientists and beyond the limits of prediction. Such changes include the possibility of abrupt changes in the circulation of the oceans with profound but unpredictable further consequences for climates regionally and globally.

Effects of a rapid warming extend to abrupt, continuous changes in the climatic zones of the earth sufficient to cause widespread mortality of forest trees at the warmer and drier limits of their ranges. Fire and disease will add to the damage to forests, speeding the release of additional stocks of carbon in plants and soils into the atmosphere. The stocks of carbon available for mobilization in the northern hemisphere are large, approximating the amount in the atmosphere currently. The effects will speed the warming.

The changes in climate are more rapid than trees or other plants migrate or forests replace themselves. The effect is the systematic impoverishment of forests in the middle and higher latitudes, including the loss of species, the destruction of plant and animal communities in parks and biotic reserves, and an increase in the frequency of diseases in residual trees and other plants. The speed of the changes in climate is the key: the warming is expected to be more rapid by a factor of ten or more than biotic processes capable of accommodating the changes. A maximum rate of warming of 0.5-1.0 degrees C per century is closer to what has occurred in the past and is advanced as a

reasonable objective if the warming is to be deflected.

The timing of the changes depends on the speed of the warming. It is reasonable to assume that the changes are underway at present and that they will become conspicuous over the next years as increased mortality of trees and other species over large areas as effects accumulate. The observations will be similar to those currently being made in forests affected by the complex of factors commonly labelled "acid rain".

The warming can be deflected or controlled only by controlling the composition of the atmosphere. A reduction in the emissions of carbon dioxide is the first step. Three mechanisms are immdediately available:

(1) reduction in the use of fossil fuels;

(2) reduction in rates of deforestation;

(3) reforestation of large areas to gain time to shift to renewable sources of energy.

Present indications are that a 50% reduction in use of fossil fuels globally coupled with prevention of further deforestation would stabilize the carbon dioxide content of the the atmosphere at present and might lead to a year-by-year reduction in the carbon dioxide content of the atmosphere of 0.5-1.0 ppm for atleast the first few years.

Such steps are appropriate and possible; they would have important further benefits in reducing other serious environmental problems such as acid rain, ozone pollution and various other toxins to plants and people, all caused by the over-use of fossil fuels.

The challenge is not one of simply muddling through a minor elevation of temperatures globally but of entering a period of continuous, accelerating global warming at rates not previous experienced by humans and well in excess of the rates at which the vegetation zones of the earth can be expected to migrate. While the effects outlined here will remain speculative until they are proven or disproven by global reality, they are well within the realm of reality in the eyes of experienced ecologists. The one further fact taught by recent experience with the issues of environment is that the earth remains full of surprises, sometimes unpleasant ones. Global issues are full of surprises and are often beyond the normal limits of scientific research and certain prediction. Uner such circumstances great caution seem appropriate before committing the world to irreversible changes of unknown magnitude and effects.

Chlorine Chemistry in the Antarctic Stratosphere

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Introduction

The appearance of the Antarctic ozone "hole" in the late 1970s, and its rapid deepening through the 1980s[1] has focused attention on the special characteristics of Antarctic chemistry and meteorology, and inspired many theoretical proposals to account for this unprecedented loss of 50% or more of the total ozone within a few weeks each September.[2-6] The National Ozone Expedition (NOZE) in 1986 discovered widespread evidence of unusual chlorine chemistry in the Antarctic stratosphere,[7] and led its scientific members to conclude that this chemistry was the primary cause of the recent Antarctic ozone losses. The second NOZE expedition and the NASA aircraft investigations over Antarctica from the base in Punta Arenas, Chile, have greatly expanded the data base, and have led to firm statements that the increase of anthropogenic chlorine, primarily from the use of chlorofluorocarbon (CFC) gases, is an integral factor in this ozone loss.[8] Scientific interest in these Antarctic discoveries now includes both the complete, detailed understanding of the south polar regional chemistry, and the applicability of these results to the Arctic, and to the stratosphere of the temperate and tropic zones.

Chlorine Chemistry in the Troposphere

The only important sources for chlorine in the stratosphere are organochlorine molecules released at the earth's surface, either by nature or by the activities of man.[9-11] Comprehensive measurements of the concentrations of chlorinated compounds in the atmosphere have been available for less than two decades (beginning with the introduction of the chlorine-sensitive electron capture detector for the assay of tropospheric air). Within this time period, the only important current contributor to the global atmospheric chlorine balance which is <u>not</u> entirely anthropogenic in origin is methyl chloride, CH_3Cl. Its measured concentrations in the atmosphere have remained essentially constant over the past 15 years at a mixing ratio of about 0.6 parts per billion by volume (ppbv), as shown in Figure 1. It is plausible to believe that the total organochlorine concentration of the global troposphere in the year 1900 was no larger than 0.6 ppbv, with CH_3Cl the only important contributor. Some sources for methyl chloride have been qualitatively identified, such as oceanic kelp beds, but its quantitative balance in nature is not fully understood. During the second half of the 20th century, the concentrations of anthropogenic chlorine compounds have risen very rapidly, greatly exceeding the amounts of chlorine previously present naturally. The first important highly volatile chlorinated molecule to be introduced was carbon tetrachloride, CCl_4, which found widespread use as a cleaning agent in the 1940s and 1950s. The next was dichlorodifluoromethane, CCl_2F_2, developed first as a refrigerant, and later in a mixture with trichlorofluoromethane, CCl_3F, as the propellant gas in aerosol sprays. Many members of this CFC family of gases now find advantageous uses in our technological, industrialized society, including the blowing of polyurethane plastic foam. Trichlorotrifluoroethane, CCl_2FCClF_2, deserves special mention

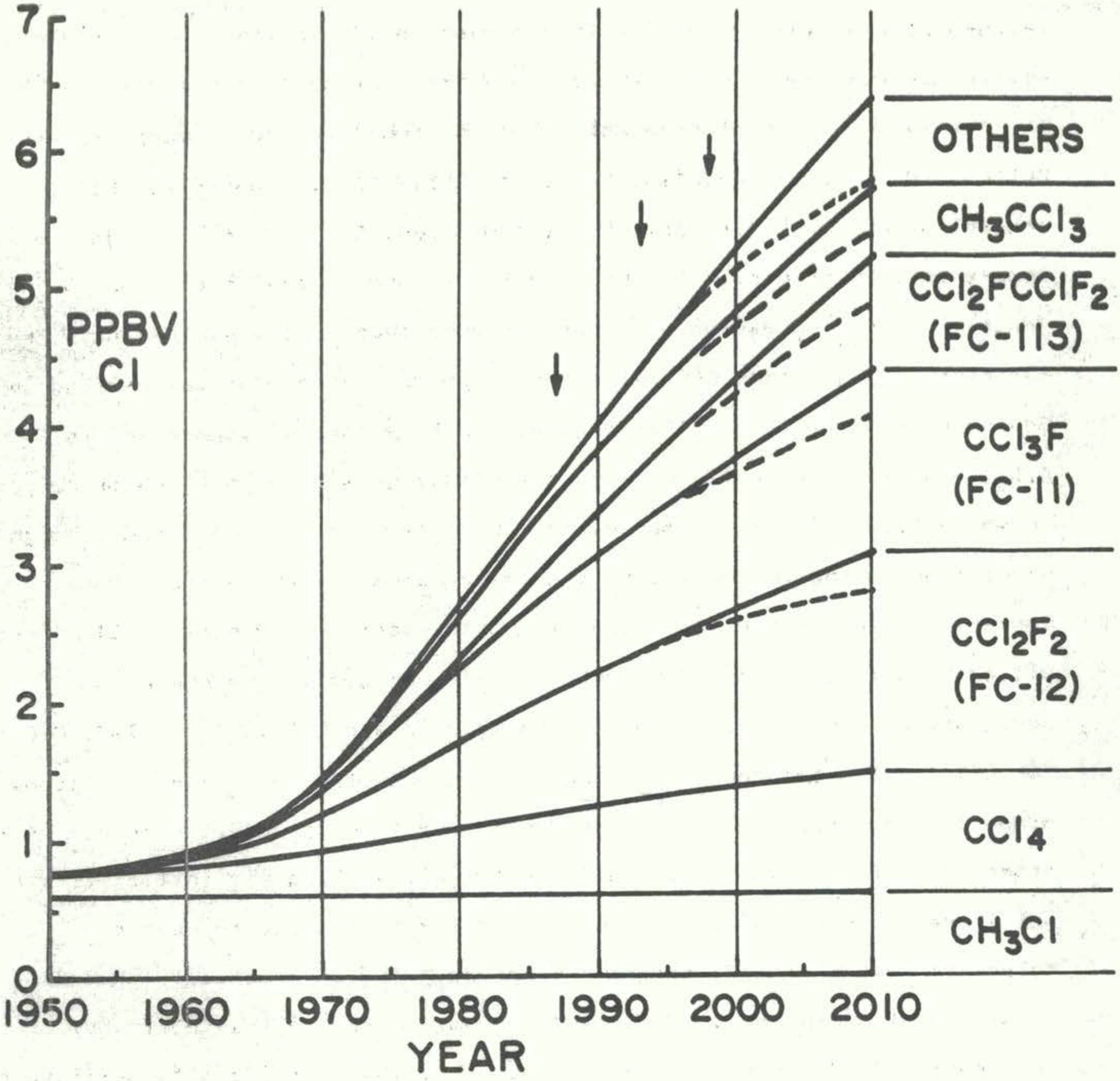


Figure 1. Concentrations of Organochlorine Compounds in the Northern Hemisphere Troposphere, 1950-2010. The three arrows point to: (a) the present date; (b) proposed UNEP date for 20% reduction in CFC emissions; (c) proposed UNEP date for 50% reduction in CFC emissions. Solid lines for years after 1988 indicate concentrations with constant emissions at 1987 levels. Dashed lines indicate concentrations with emission cutbacks at times indicated in (b) and (c) above.

because of the rapid expansion in the past decade in its use for cleaning electronic components such as semi-conductor chips.

The major organochlorine molecules now found in the troposphere are CCl_2F_2, CCl_3F, CCl_4, CH_3CCl_3, CH_3Cl and CCl_2FCClF_2. The total chlorine concentration (e.g. 0.4 ppbv CCl_2F_2 = 0.8 ppbv Cl) in the northern hemisphere in 1988 exceeds 3.5 ppbv (about 10% more in the north than in the south), and is increasing at a rate of more than 1 ppbv per decade. The restrictions on future CFC emissions proposed in the Montreal meeting in September 1987 will have little effect on this rate of growth before 2000 A.D., and even then will not stop the steady growth in total chlorine, as shown in Figure 1. In commerce, the CFCs are usually identified through a special numbering scheme and by trademark names, of which the DuPont Company's Freon is the best known in North America. (Others: ICI, Arcton; Allied-Signal, Genetron; Farbwerke Hoechst, Frigen). The numerical designations for the most important molecules are CFC-11 for CCl_3F; CFC-12 for CCl_2F_2; CFC-113 for CCl_2FCClF_2. (Hundreds digit = number of C atoms minus 1; Tens digit = number of H atoms plus 1; Units digit = number of F atoms; e.g. for CCl_2F_2, 0,1,and 2, or 12, not writing the initial zero.)

Three important general processes ("sinks") operate to destroy molecules newly released to the atmosphere.[9,11] If a molecule absorbs solar radiation in the visible (400-700 nm) or near ultraviolet (UV) wavelengths (293-400 nm), then this absorbed energy is usually sufficient to photodissociate the molecule. An example is molecular chlorine, Cl_2, whose green color indicates that it absorbs visible radiation, and whose atmospheric lifetime in the sunlight is about one hour. Many compounds such as HCl, transparent in the visible and near-UV, are soluble in raindrops and are removed by rainfall, usually within a few weeks. The third major tropospheric sink is oxidation through attack by hydroxyl radicals, as shown in reaction (1) with methane.

$$HO + CH_4 \longrightarrow H_2O + CH_3 \qquad (1)$$

The key to the stratospheric importance of molecules such as CCl_2F_2 is that they are not affected by any of these three processes: transparent to solar radiation in the visible, and in the UV from 400 nm to about 230 nm; insoluble in water; and inert toward HO attack because of the absence of reactive H atoms in the molecule. Without any effective tropospheric removal processes, the <u>perhalo</u> <u>saturated</u> CFCs survive for many decades in the atmosphere, and eventually rise into the stratosphere where they can be decomposed by solar UV radiation at wavelengths in the 190-230 nm range. In 1974, Molina and Rowland estimated the atmospheric lifetime of CCl_3F as 40 to 80 years, and that of CCl_2F_2 as 75 to 150 years.[9] Current assays of the existing concentrations coupled with atmospheric modeling indicate lifetimes of about 75 years for CCl_3F and 120-140 years for CCl_2F_2.[11] The atmospheric lifetime of CCl_2FCClF_2 (whose worldwide use was very minor in 1974) is calculated to be about 100 years.

Not all halocarbon molecules are severe threats to stratospheric ozone. Many such as CH_2ClCH_2Cl are produced in very large quantities, but are not released to the atmosphere. (It is instead converted in industrial plants into $CH_2{=}CHCl$, and then into the plastic PVC, polyvinyl chloride). Among those emitted to the atmosphere are many with shorter atmospheric lifetimes because of chemical reaction with HO, including $CCl_2{=}CCl_2$ (not saturated because of its C=C double bond), CH_3CCl_3 and $CHClF_2$ (CFC-22)--not perhalo because of the presence of the reactive H atoms. The oxidation of the latter two in the troposphere requires about 6 or 7 years for CH_3CCl_3 in (2), and 20 years for $CHClF_2$ in (3). The rate of removal through HO attack can be estimated from the relative rate constants for such reactions measured in the laboratory, with (3) the accepted standard.

$$HO + CHClF_2 \longrightarrow H_2O + CClF_2 \qquad (2)$$

$$HO + CH_3CCl_3 \longrightarrow H_2O + C_2H_2Cl_3 \qquad (3)$$

The yearly emissions of CFCs to the atmosphere have risen rapidly over the past 25 years, and the long atmospheric lifetimes insure ever increasing mixing ratios in the troposphere. The tropospheric organochlorine concentrations of the individual molecules are shown in Figure 1 for the last half of the 20th century. These data are based on actual measurements from about 1972 to the present, and are extrapolated to the past and to the future on the basis of estimates of current industrial production rates of the individual molecules.

Chlorine Chemistry in the Temperate and Tropic Stratosphere

Solar radiation arriving at the top of the atmosphere includes very short wavelength UV radiation, but only wavelengths longer than 293 nm actually reach the earth's surface. The two primary agents for absorbing the shorter wavelength UV are O_2 which constitutes 20.9% of the atmosphere, and ozone, O_3, which is present only in trace concentrations averaging about 0.3 parts per million by volume (ppmv). Solar UV with wavelengths shorter than 242 nm causes the photodissociation of O_2 in (4), and is the major removal process for solar UV with wavelengths shorter than 200 nm. The O atoms released in (4) usually combine with a molecule of O_2 to form O_3, as in (5), transferring the extra energy released during chemical bond formation to the other molecules (M) of the atmosphere. Between 220 nm and

300 nm, most of the solar UV is absorbed by O_3 in (6), only to have the

$$O_2 + UV \rightarrow O + O \quad (4)$$

$$O + O_2 + M \rightarrow O_3 + M \quad (5)$$

$$O_3 + UV \rightarrow O + O_2 \quad (6)$$

released O atoms recombine with O_2 in (5). This combination of (6) and (5) converts the incoming solar UV energy into heat, and warms up the surrounding atmosphere. This process introduces a heat source in the upper part of the ozone layer, causing warmer temperatures at an altitude of 50 km than found below at 20 to 30 km. This UV absorption actually creates the stratosphere with its maximum temperature near 50 km.

Occasionally, the O atoms from (6) are intercepted by O_3 instead of by O_2, with the result that both O and O_3 are converted back to O_2 in (7).

$$O + O_3 \rightarrow O_2 + O_2 \quad (7)$$

The set of reactions from (4) to (7) is sometimes described as the "pure oxygen" reactions because they involve no chemical element other than oxygen, or as the Chapman reactions, from the geophysicist who first suggested in 1930 this origin for stratospheric ozone. The concentrations of ozone and atomic oxygen are often combined in the term "odd oxygen" (i.e. O_1 and O_3, as distinct from O_2): reaction (4) increases the concentration of odd oxygen by + 2. Reactions (5) and (6) both cause no change, while (7) changes odd oxygen by -2. This counting scheme emphasizes that reaction (5) is not really a source of net additional O_3 when preceded by (6). The only real source of additional ozone in the stratosphere must be one which produces more odd oxygen, and reaction (4) is alone in this.

The removal of odd oxygen can be accomplished as well by several free radical catalytic chain reactions, including those identified as the HO_x,

NO_x and ClO_x chains. The NO_x and ClO_x chains operate in the stratosphere through reactions (8) through (11). Each of these reactions represents a

$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2} \qquad (8)$$

$$\mathrm{NO_2} + \mathrm{O} \rightarrow \mathrm{NO} + \mathrm{O_2} \qquad (9)$$

$$\mathrm{Cl} + \mathrm{O_3} \rightarrow \mathrm{ClO} + \mathrm{O_2} \qquad (10)$$

$$\mathrm{ClO} + \mathrm{O} \rightarrow \mathrm{Cl} + \mathrm{O_2} \qquad (11)$$

-1 change in odd oxygen, and the combinations [(8) + (9)] or [(10) + (11)] return the initial reactant (NO or Cl) to complete the cycle. The molecules NO and Cl act as catalysts because they assist the chemical change of O and O_3 into O_2 + O_2 without being permanently altered themselves. Moreover, these reactions occur extremely rapidly because NO, NO_2, Cl and ClO are free radicals (i.e. having odd numbers of electrons--15, 23, 17, and 25), and the last, unpaired electron confers unusual chemical reactivity.

Free radical chains persist through many cycles before the chains are terminated by the combination of two free radical chain carriers to form temporary reservoir molecules, as with nitric acid in (12), chlorine nitrate in (13), and HOCl in (14). The chemical sequences can also be

$$\mathrm{HO} + \mathrm{NO_2} + \mathrm{M} \rightarrow \mathrm{HONO_2} + \mathrm{M} \qquad (12)$$

$$\mathrm{ClO} + \mathrm{NO_2} + \mathrm{M} \rightarrow \mathrm{ClONO_2} + \mathrm{M} \qquad (13)$$

$$\mathrm{ClO} + \mathrm{HO_2} \rightarrow \mathrm{HOCl} + \mathrm{O_2} \qquad (14)$$

intermixed or diverted from one chain to another through reactions such as those shown in (15) and (16). The depletion of ozone in the stratosphere

$$\mathrm{ClO} + \mathrm{NO} \rightarrow \mathrm{Cl} + \mathrm{NO_2} \qquad (15)$$

$$\mathrm{Cl} + \mathrm{CH_4} \rightarrow \mathrm{HCl} + \mathrm{CH_3} \qquad (16)$$

over temperate and tropic regions is accomplished by the Cl/ClO chain of (10) and (11), with interruptions through the formation of the temporary reservoirs HCl, $ClONO_2$ and HOCl. These chlorine reservoirs can in turn be destroyed with the release of atomic Cl by reactions (17) to (19). The stratospheric chemistry of chlorine is summarized in Figure 2.

$$HO + HCl \text{ --> } Cl + H_2O \qquad (17)$$

$$ClONO_2 + h\nu \text{ --> } Cl + NO_3 \qquad (18)$$

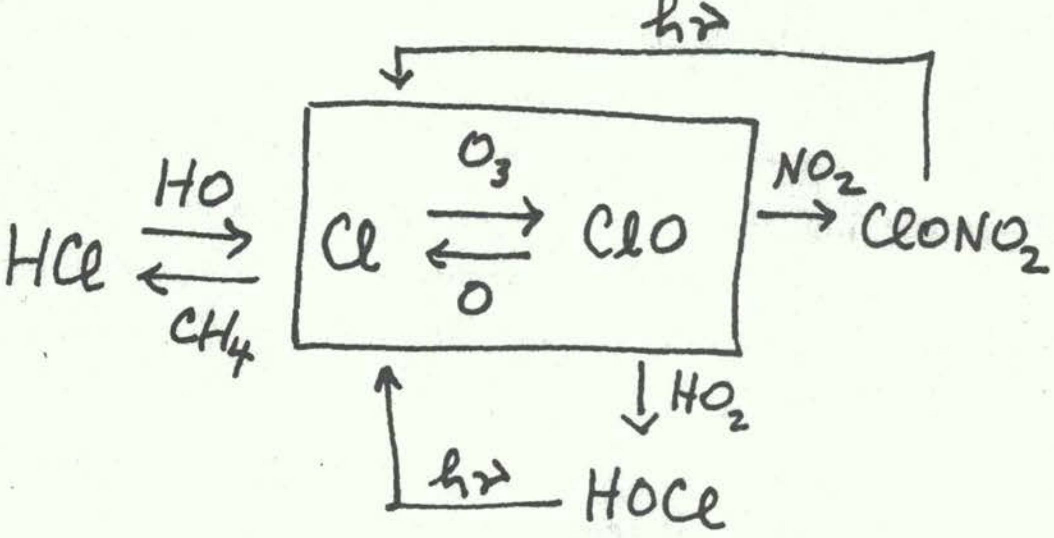
$$HOCl + h\nu \text{ --> } Cl + HO \qquad (19)$$

Reaction (10) requires only one or two seconds in the stratosphere because of the high concentrations of ozone, while reaction (11) takes about one minute in the upper stratosphere where the O atom concentration is as high as 10^9 cm^{-3} above 40 km. The ClO_x chain is less effective in depleting ozone at lower altitudes because the O atom concentration decreases rapidly down through the atmosphere, with peak ozone loss rates by the ClO_x chain found between altitudes of 35 and 45 km. In the upper stratosphere, the cycle of (10) plus (11) can run for as many as 1000 cycles--part of one day--before being interrupted by the formation of one of the reservoir molecules. Then, after hours (HOCl; $ClONO_2$) or a few days (HCl) in that form, the Cl atom is again released and the ClO_x chain runs for another 1000 cycles, etc. Over the course of the year or two required for the randomly wandering chlorine atoms (in changing chemical form) to reach the troposphere and ultimate rainout as hydrochloric acid, the average chlorine atom will remove about 100,000 molecules of odd oxygen.

Stratospheric Chemistry of Chlorofluorocarbons

The chlorofluorocarbon molecules absorb UV radiation with wavelengths shorter than about 230 nm, and none of that radiation penetrates to the troposphere because of its absorption at higher altitudes by O_2 and O_3. The perhalo CFCs can thus survive indefinitely--presumably many hundreds of

FIG. 2



UPPER STRATOSPHERE
CHLORINE CHEMISTRY

UPPER

$$\begin{array}{l} Cl + O_3 \rightarrow ClO + O_2 \\ ClO + O \rightarrow Cl + O_2 \\ \hline O + O_3 \rightarrow O_2 + O_2 \end{array}$$

NET LOSS
OF OZONE
AT 40 km

MID

$$\begin{array}{l} Cl + O_3 \rightarrow ClO + O_2 \\ ClO + NO \rightarrow Cl + NO_2 \\ NO_2 + h\nu \rightarrow NO + O \\ O + O_2 \xrightarrow{M} O_3 \\ \hline \end{array}$$

NO NET CHANGE
AT 25-30 km

years--in the lower atmosphere. Before any photodecomposition can occur, the CFC molecules must first diffuse above the other UV absorbers--for instance, to 30 km with about 80% of O_3 and 98% of O_2 lying below. However, when they do reach the upper stratosphere, the CFCs are exposed to very short wavelength UV which they <u>can</u> absorb, and which then lead to their decomposition, as in (20). In a relatively short time after the

$$CCl_2F_2 + UV \longrightarrow Cl + CClF_2 \qquad (20)$$

initial photolysis, the radical fragment ($CClF_2$ in reaction 20) also releases the additional halogen atoms, and they immediately initiate attack on nearby ozone molecules. (While F atoms readily attack O_3, the FO_x chain analogous to (10) and (11) is soon interrupted by the reaction $F + CH_4 \longrightarrow HF + CH_3$, and the very stable molecule HF is a <u>permanent</u> <u>reservoir</u> carrying the F atom without further change into tropospheric rainfall).

The concentration of chlorinated molecules in the stratosphere follows their concentrations in the troposphere after a few years' delay for upward transport and poleward diffusion. The rapid increase in the concentrations of CCl_2F_2, CCl_3F, CCl_4 and CCl_2FCClF_2 in the past two decades is expected to continue into the future (Figure 1), and the amounts of stratospheric chlorine will increase correspondingly. In contrast, if the atmospheric emissions of CH_3CCl_3 continue at the present yearly rates (about 500 kilotons/year), its tropospheric concentration will not increase too much more because of its 7 year atmospheric lifetime controlled by reaction (3).[12,13] Similarly, the other molecules with important tropospheric sinks--such as (2) for $CHClF_2$--will not accumulate to the same extent as the perhalo compounds.

Antarctic Meteorology: Polar Vortex and Polar Stratospheric Clouds

The meteorologies of the two polar regions are different from one another, and from the general pattern of the temperate and tropical zones. A closed polar vortex exists during the Antarctic winter such that the air which is over the polar region circulates in the darkness during the long winter, slowly radiating to outer space. As a consequence, the winter Antarctic stratosphere reaches extremely cold temperatures as low as -90°C, low enough to cause the formation of clouds--the PSCs, or polar stratospheric clouds. The Arctic winter vortex is not as constrained, with air parcels moving across the polar regions and back out into low sunlight. Because the individual air masses do not remain in the darkness for months without respite, the Arctic winter stratospheric temperatures are normally higher than in the Antarctic. Polar stratospheric clouds are known in the Arctic, but are much less frequent than in the Antarctic.[14]

In the presence of PSCs, some chemical reactions can occur which would be much slower without the particulate surfaces to facilitate these "heterogeneous" reactions.[10,14] The chemical processes described in previous sections have all been homogeneous gas phase reactions initiated either by the absorption of solar radiation by a gaseous compound, or by especially energetic thermal collisions between freely moving gaseous molecules. In the temperate zone NO reacts with O_3 to form NO_2 by (8), and NO_2 reacts with O_3 to form NO_3. Because both NO_2 and NO_3 are decomposed by sunlight, NO continues to exist during daylight. After dusk, however, NO_2 and NO_3 no longer are photodecomposed, and can further react with one another to form N_2O_5. In the early morning sunlight of temperate zone latitudes, successive photolytic processes convert N_2O_5 back through NO_3

and NO_2, and NO reappears in substantial concentrations. During the Antarctic winter, however, N_2O_5 reacts with H_2O on the PSC particles to form nitric acid by reaction (21), and the nitric acid remains condensed on the particle surface.[9] In this way, the concentrations of free nitrogen

$$H_2O + N_2O_5 \xrightarrow{PSC} 2\ HONO_2 \qquad (21)$$

oxides as NO, NO_2, NO_3 and N_2O_5 are driven down to negligible levels in the polar darkness, and do not return to normal levels until after the PSCs themselves disappear with the springtime warming of the Antarctic stratosphere. The gaseous nitrogen oxides actually do not reappear for an additional one or two weeks until the $HONO_2$ released from an evaporating PSC particle has been destroyed, either by HO attack or by UV photolysis. It seems quite likely that this process of "denitrifying" the winter Antarctic stratosphere has been occurring in a similar fashion for centuries.

<u>Heterogeneous Chlorine Chemistry on PSC Surfaces</u>

Now, however, the entire atmosphere has far higher concentrations of chlorine compounds than were present as recently as the mid-1970s (Figure 1). The molecule $ClONO_2$ resembles N_2O_5 and $HONO_2$ ($Cl-O-NO_2$, $H-O-NO_2$, $O_2N-O-NO_2$) and reaction (22) can also occur on the exposed PSC cloud surfaces, in analogy to (21). The PSC surfaces can also catalyze the reaction of <u>two</u> temporary reservoir molecules with one another, as with HCl and $ClONO_2$ in (23).[10] In both cases, the nitric acid remains attached to the particle, but the chlorinated species (HOCl or Cl_2) escape back into the gas phase.[16]

$$H_2O + ClONO_2 \xrightarrow{PSC} HOCl + HONO_2 \qquad (22)$$

$$HCl + ClONO_2 \xrightarrow{PSC} Cl_2 + HONO_2 \qquad (23)$$

The earth's stratosphere is extremely dry, with amounts of H_2O varying only between 3 and 6 ppmv. The H_2O concentration is even more uniform than suggested by those limits because the <u>total</u> amount of hydrogen in the stratosphere is approximately constant everywhere at about 12 ppmv of H (the equivalent of 6 ppmv H_2O). The only two important avenues for the delivery of H to the stratosphere are the direct upward transport through the tropopause of H_2O and CH_4, with the eventual subsequent oxidation of the latter to H_2O. The total hydrogen in the stratosphere is approximately the equivalent to the sum of 3 ppmv H_2O and 1.5 ppmv CH_4, the amount found in the troposphere in the late 1970s. The only place cold enough (-95° to -90°C) to freeze out the H_2O concentration of air rising into the stratosphere to 3 ppmv is found at the tropical tropopause. Air which is eventually found at 20 km above Antarctica first enters the stratosphere in the tropics with about 3 ppmv H_2O and 1.5 ppmv CH_4 and then spreads toward both poles. By the time these air parcels are found in the polar regions, a very large fraction of CH_4 has been oxidized and the H_2O concentration has moved toward 6 ppmv. (Most molecules of CCl_3F, CCl_2F_2, CCl_2FCClF_2, etc., in these air masses have also been decomposed and converted to other forms of chlorine.) The CH_4 concentration in the troposphere in 1988 is now about 1.7 ppmv, so that air arriving over the Antarctic in the year 2000 will probably have another 0.4 ppmv H_2O more than today.[17] In contrast, the concentration of 200 year old air preserved in glacial ice cores is only 0.7-0.8 ppmv, less than half of the present concentration.[11] Preliminary results from the 1987 aircraft expedition indicate that sufficient H_2O has condensed into the PSCs to reduce the gaseous H_2O level well below the usual 3 to 6 ppmv, making the Antarctic stratosphere exceptionally dry.[8]

The arrival of the first sunlight of the Antarctic spring finds air parcels in the lower stratosphere for which: (a) the nitrogen oxides have been converted to $HONO_2$ and sequestered on the PSCs; (b) most CH_4 has already been oxidized; and (c) the existing chlorine content is usually found as gaseous Cl_2 or HOCl instead of the prominent temperate zone temporary reservoirs, HCl and $ClONO_2$. The sunlight then photolyzes HOCl and Cl_2, with the release of atomic Cl which then immediately attacks ozone by (10). A major fraction of all Cl in these air masses is available for reaction in ClO_x chains. In the temperate zone stratosphere, the chemical reactions which usually interrupt the ClO_x chain (See Figure 2) are (13), ClO with NO_2 to form $ClONO_2$, and (16), Cl with CH_4. In the Antarctic, however, NO_2 and the other nitrogen oxides are tied up in the PSCs as $HONO_2$, and almost all of the CH_4 has been oxidized on its long path since entry into the stratosphere at the tropical tropopause. The remaining CH_4 is at a very low temperature, further slowing the rate of reaction with atomic Cl. Under these conditions, chlorine is not easily diverted from free radical reactions, and can react in long chains for a period of several weeks, including most of September. Measurements from the ground at McMurdo, Antarctica,[7] and by high altitude research aircraft[8] have confirmed concentrations of ClO as high as 1 ppbv in the springtime Antarctic stratospheric vortex--concentrations as much as 500 times higher than found at the same altitudes over temperate latitudes. These concentrations represent <u>more</u> chlorine as ClO than was present in <u>all</u> chemical forms in

1960 (Figure 1), so that an important fraction of the ClO <u>must</u> have come from the organochlorine compounds released into the atmosphere by man.

A quantitative chemical problem remains for the completion of the ClO_x chain because the O atoms needed for reaction (11) are relatively scarce in the lower stratosphere during the early Antarctic spring, sufficiently so that long delays would be required for the second step of that cycle. Under the Antarctic conditions, alternate ozone-depleting ClO_x chains must exist which do not require O atoms for completion. One such chain involves reaction with HO_2, as in reactions (10), (19), (24) and (25), with a net of $2\ O_3 \dashrightarrow 3\ O_2$.[2]

$$HO_2 + ClO \longrightarrow HOCl + O_2 \tag{24}$$

$$HOCl + h\nu \longrightarrow Cl + HO \tag{19}$$

$$Cl + O_3 \longrightarrow ClO + O_2 \tag{10}$$

$$HO + O_3 \longrightarrow HO_2 + O_2 \tag{25}$$

Two other analogous chains involving ClO_x have also been suggested as contributing to the depletion of ozone over Antarctica. In one,[4] two ClO radicals are assumed to react with one another to form a dimeric Cl_2O_2 in (26), followed by decomposition either thermally or photochemically to form Cl plus ClOO in (27a). The radical ClOO is itself thermally unstable, and will break up to $Cl + O_2$ to complete the cycle, and free both Cl atoms to

$$ClO + ClO \longrightarrow (ClO)_2 \tag{26}$$

$$(ClO)_2 + h\nu \longrightarrow Cl + ClOO \longrightarrow 2\ Cl + O_2 \tag{27a}$$

$$(ClO)_2 + h\nu \longrightarrow Cl + OClO \tag{27b}$$

react again with ozone. In the other proposed chain,[3] the radical BrO formed in the attack of atomic Br on O_3 in (29) is the reaction partner for ClO in (28). The reaction of BrO with ClO can lead directly to Br plus Cl plus O_2 in (28a), bypassing the need for the photochemical decomposition

$$BrO + ClO \longrightarrow Br + ClOO \longrightarrow Br + Cl + O_2 \quad (28a)$$

$$BrO + ClO \longrightarrow Br + OClO \quad (28b)$$

$$Br + O_3 \longrightarrow BrO + O_2 \quad (29)$$

steps required for HOCl in the first sequence and $(ClO)_2$ in the second. The structure of the $(ClO)_2$ dimer is uncertain at present, and open-chain molecules with the structures Cl-O-O-Cl and Cl-O-Cl-O may both exist. In the latter case, photolysis would lead to Cl and OClO; OClO can also be formed by the alternate pathway (28b) of BrO with ClO. Measurements from the ground in Antarctica have established time the presence of OClO as a component of the early spring stratosphere there,[7] while temperate zone measurements with the same instrument have shown this molecule not to be detectable in the normal stratosphere.

Aircraft measurements in September 1987 have shown BrO not to be present in the Antarctic stratosphere at the levels needed for it to be the dominant ozone removal process.[8] However, with concentrations of BrO in the range of 6 pptv, its reaction with ClO can still be an important contributor to the overall removal of ozone from the Antarctic stratosphere.

Stratospheric Ozone Depletion at Other Latitudes

The combination of chemistry and meteorology in the Antarctic springtime is obviously unique because the loss of 50% of total ozone in one month has not been observed in other latitudes. The conditions producing PSCs in abundance throughout the winter are very specific to the Antarctic, and insure the availability of large surface areas for possible catalysis of heterogeneous reactions. However, the PSC-aided reactions of H_2O with N_2O_5 and $ClONO_2$ and of HCl with $ClONO_2$ all take place very readily on a wide variety of experimental laboratory surfaces,[13,14] including most of the special "inert" surfaces devised over the years for suppression of surface catalyzed chemistry. The occurrence of the same reactions on Arctic PSC surfaces seems probable whenever these surfaces are available, although how far they can proceed in a week rather than several months has not yet been established. Their possible occurrence on the sporadically available volcanic clouds, or on the ever present background stratospheric sulfate layer particles needs thorough investigation. Because little is known of the actual structure of such particles, and laboratory duplication of surfaces is notoriously difficult in any case, such tests will probably need to be carried out in the stratosphere itself. Without much further information about the contributions of these reactions to overall global ozone depletion, conclusions about future ozone depletion based on atmospheric models using only the present set of strictly homogeneous gas phase reactions are quite likely to be seriously in error.

Experimental observations have shown losses of several percent for ozone in the temperate zone upper stratosphere near 40 km, consistent with both the expected altitude dependence and quantitative losses anticipated for the ClO_x chain. Recent study of total ozone measurements have also shown preferential losses in the winter for ground-based stations in Switzerland (Arosa) and the northern United States (Bismarck, North Dakota; Caribou, Maine).[10] The possible contributions of heterogeneous reactions to this wintertime ozone loss in the northern hemisphere are currently being evaluated.

Acknowledgments.

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<u>References (continued).</u>

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(7) Four research groups were members of the NOZE Expedition, and the following references presented some of their initial results:

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STATEMENT OF

DR. ROBERT T. WATSON *

EARTH SCIENCE AND APPLICATIONS DIVISION

OFFICE OF SPACE SCIENCE AND APPLICATIONS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

U. S. HOUSE OF REPRESENTATIVES

Mr. Chairman and Members of the Committee:

I am pleased to be here today to discuss our current understanding of the cause or causes of the observed decrease in ozone over Antarctica during springtime since the late 1970's.

In my testimony today, I will speak on behalf of the scientists and team who participated in the Airborne Antarctic Ozone Experiment, using as a basis the statement of findings prepared by the science team in Punta Arenas, Chile. Before doing so, however, I would like to stress that the tremendous success of this mission is the direct result of the outstanding cooperation and effort of the large and diverse group of participants in this intense and challenging campaign. The success of the mission has exceeded any of our prior expectations, and for this credit must go to not only the scientists, but to the flight, ground and support teams associated with the project.

This scientific summary statement was prepared by the scientists who went to Punta Arenas, Chile to study the Antarctic ozone hole. This summary represents the views of the scientists themselves and not necessarily those of the cosponsoring organizations. The findings that will be presented are preliminary. Under normal circumstances, scientists studying such a complex scientific issue would take many months to years to disclose their initial findings. However, the issue of ozone perturbation is one of justifiable public concern, and hence the public should be kept abreast of the current scientific thinking. It is in this spirit that we would like to share our provisional picture of the Antarctic springtime ozone hole. Furthermore, this will help to stimulate the scientific inquiry and debate that can only lead to an improved and timely understanding of the phenomenon. A much more complete and final interpretation of our findings will be forthcoming after a planned intensive series of scientific meetings and the submittal of a group of scientific papers to the peer review process. This procedure will occur within the next six months.

Description of Goals and Objectives of the Mission

Three basic theories have been proposed to explain the observed decrease in spring-time Antarctic ozone that has been occurring since the late-1970's. One class of theories suggest

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* Editors Note: After delivering this testimony Thursday morning, October 29, 1987, Dr. Watson chaired a panel discussion on the Antarctic ozone problem at the concluding luncheon of the conference. Panelists also included Dr. Adrian Tuck of NOAA and Dr. F. Sherwood Rowland of the University of California Irvine.

that the hole is caused by the human activity of loading the atmosphere with chlorinated and brominated chemicals. Chlorofluorocarbons (CFC's) and Halons are contributing increasing levels of chlorine and bromine to the atmosphere. These compounds could then efficiently destroy stratospheric ozone in the Antarctic environment because of the special geophysical conditions that exist in this region of the atmosphere, i.e. a contained polar vortex (an isolated air mass), cold temperatures, and the presence of polar stratospheric clouds. A second class of theories suggests that there have been changes in the circulation of the atmosphere, which now transports ozone-poor air into Antarctica. A third theory postulates solar and cosmic ray induced, periodically enhanced abundances of oxides of nitrogen, which can cyclically destroy ozone.

The NSF-coordinated expedition to the McMurdo station in Antarctica last year was exceptionally successful in increasing our understanding of the Antarctic ozone hole. In conjunction with other experiments, this ground based effort demonstrated the recurrence of the ozone hole, the altitude over which ozone was depleted, that chlorine and nitrogen chemistry was highly perturbed relative to that observed at mid-latitudes, and that the solar cycle theory is an unlikely explanation. However, the McMurdo data were insufficient to distinguish adequately between the relative contributions of the first two classes of theories. Therefore, the goal of the present airborne campaign is to improve our understanding of the relative contributions of these, and possibly other, mechanisms to the formation of the Antarctic ozone hole.

One of the key environmental issues is whether the ozone depletion observed in Antarctica will always be localized in and around Antarctica, or whether it is a precursor of future global changes. A longer term objective of this campaign is to be able to provide information relevant to answering this question.

Participants, Sponsors, and Foreign Government Support

The campaign was coordinated by the National Aeronautics and Space Administration (NASA) and cosponsored by NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Chemical Manufacturers Association (CMA). In addition, the British Meteorological Office (BMO) and the European Center for Midrange Weather Forcasting (ECMWF) provided significant contributions to the project.

Scientists, engineers, and other personnel from Harvard University, University of Denver, University of Washington, University of Colorado, National Center for Atmospheric Research, Jet Propulsion Laboratory, NASA Ames Research Center, NASA Langley Research Center, NASA Goddard Space Flight Center, NOAA Aeronomy Laboratory, the British Meteorological Office, the European Center for Medium Range Weather Forecasts (ECMWF), Centre Nationale Recherches Meteorologiques, and Atmospheric and Environmental Research, Inc. participated in this campaign. Dr. J. C. Farman of the British Antarctic Survey kindly made available Halley Bay ozonesonde data. Scientists from both Chile and Argentina were also involved.

Key participants in this campaign were also the flight and ground crews of NASA, Lockheed Corporation, and Northrop Corporation, who flew and maintained the ER-2 and DC-8 research aircraft under very challenging conditions. Research and Data Systems, Corp. provided the necessary telecommunication links and support.

The Chilean government hosted the airborne campaign, which was based out of Punta Arenas. The Chilean Air Force supplied the facilities and logistical support. The Chilean

Antarctic Institute provided advice regarding the study area. In addition, invaluable assistance was provided by the Direccion General De Aeronautica Civil, and the National Meteorologic Service of Chile.

Other countries also helped: Panama, Costa Rica, Peru, and Ecuador cooperated with the overflights necessary for the transit from the United States to Chile. The government of Argentina offered alternate landing fields for the aircraft as they returned from their Antarctic missions. The National Meteorological Service of Argentina furnished data from Marambio. Lastly, the government of New Zealand assisted with the transcontinental Antarctic flight by the DC-8 that was part of the return to the United States.

Description of Campaign

The Airborne Antarctic Ozone Campaign succeeded in making 12 flights of the high altitude ER-2 aircraft, and 13 flights of the DC-8 medium altitude aircraft over Antarctica. The ER-2 typically operated at geometric altitudes relative to sea level between 12.0 and 18.7 km and flew to 72 degrees South along the Palmer Peninsula. The DC-8 operated at altitudes up to about 10 km and with its long range capability was able to reach the South Pole on several occasions, and returned to the United States via New Zealand after crossing the Antarctic continent. The project had available to it Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) images of the total ozone column of the southern hemisphere within a day of observation and of the orbits passing over the region of the Antarctic peninsula within 2 to 4 hours of observation. Aerosol and cloud extinction data were also available from the Nimbus-7 Stratospheric Aerosol Measurement (SAM II) and Stratospheric Aerosol and Gas Experiment (SAGE II) on the Earth Radiation Budget Satellite. The latter also provided ozone measurements. Twice daily analyses and forecasts of winds and temperatures up to 30 mb, 22 km, for three days ahead, were provided by the BMO in chart form, plus forecasts of the trajectories of air parcels on surfaces along which air masses move. Photochemical modelling along these trajectories was done using the aircraft observations. The ECMWF provided once a day analyses and forecasts up to 30 mb for 10 days ahead. A small theory team assisted the experimental scientists with the interpretation on a day to day basis. This approach was possible because of the availability of rapid data reduction facilities and an extensive, dedicated international telecommunications network.

Detailed lists of the participants, a discussion of the theories being addressed, the approach taken in the tests of these theories, and a description of the apparatus involved are given in the Airborne Antarctic Ozone Experiment Plan (NASA and NOAA, July 1987). Copies are available on request from NASA Ames Research Center or NASA Headquarters.

Data obtained from the ER-2 and DC-8 instrumentation

The spatial and temporal distribution of a large number of relatively short-lived chemical constituents that participate in chemical reactions that affect the abundance of ozone were measured from both the ER-2 and DC-8. Instruments aboard the ER-2 resulted in measurements of the distributions of ozone (O_3), chlorine monoxide radical (ClO), bromine monoxide radical (BrO), total odd nitrogen (NO_y), nitric oxide (NO), and water (H_2O) in the vicinity of the aircraft at altitudes ranging from 12 to 18 km above the Earth's surface, well into the altitude region where ozone is undergoing depletion. Instruments aboard the DC-8 measured the abundances of H_20 and O_3 in the vicinity of the aircraft, the vertical distribution of O_3 for approximately 10 km above the aircraft, and the total column amounts of O_3, hydrochloric acid (HCl), chlorine nitrate ($ClONO_2$), chlorine dioxide (OClO), BrO, hydrofluoric acid (HF), NO, nitrogen dioxide (NO_2), nitric acid (HNO_3), as well as a number of other constituents, above the aircraft altitude.

Additionally, the temporal and spatial distributions of long-lived chemical tracers and dynamical variables were measured in order to understand atmospheric motions. These included measurements of nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons 11 ($CFCl_3$) and 12 (CF_2Cl_2), carbon tetrachloride (CCl_4), and methylchloroform (CH_3CCl_3). In-situ measurements of all of these species were made from both the ER-2 and DC-8, and column measurements of most from the DC-8. The size distribution, abundance, and composition of particles was determined by instrumentation aboard the ER-2, as well as the vertical distribution of aerosols from 12 to 28 km by the DC-8 lidar, in an effort to understand the role of heterogeneous processes. Additionally, atmospheric pressure, temperature, lapse rate, and winds were measured aboard the ER-2 to determine the state variables and dynamical structure of the atmosphere.

The project had regular ozone sonde data available from the Palmer station, the Halley Bay station, the South Pole station, and McMurdo. These define the vertical distribution of ozone at points not routinely covered by the flight tracks. Ozonesondes were launched at special times from Palmer and the South Pole to coincide with aircraft overflights of those locations.

The analyses of some of these data sets have not yet been completed, either because of the lengthy data reduction procedures required or because of the sheer volume of raw data acquired. An example of the latter is the meteorological data set, whose initial analyses had the primary goal of forecasting the flight conditions. Furthermore, many of the analyses of the chemical data sets are clearly only preliminary, to be refined by recalibration checks and more sophisticated re-analyses available at the home laboratories. As a consequence, the initial picture summarized below cannot be a balanced, complete, and final one.

Results and their relationship to theories

The processes controlling the abundance and distribution of ozone in Antarctica are complex and intertwined. However, given the successful nature of this campaign, we are now in a position to start to more fully appreciate the exquisite balance between the meteorological motions and the photochemistry. We will present our preliminary scientific findings as answers to a series of posed scientific questions that are relevant to public policy.

1) Did the springtime ozone hole occur over Antarctica in 1987?

Yes. TOMS satellite, balloon ozonesonde, and both ER-2 and DC-8 aircraft measurements of ozone showed that the springtime ozone decrease occurred again this year. TOMS showed the spatial extent of the phenomenon is continental or greater in scale and revealed the temporal change in the total column of ozone. The abundance of ozone in August and September of 1987 was lower than any previous year at all latitudes south of 60 degrees. In mid-September of this year column ozone was approximately 15% lower at both 70 and 80 degrees south than the values observed in the lowest previous year of 1985. The balloon-sonde data demonstrated that ozone was depleted in the altitude region between approximately 13 and 24 km at Halley Bay, and 15 and 24 km at Palmer. Ozone trends observed at Halley Bay and at Palmer are quite similar, with an approximate 50% decrease observed from mid-August to mid-September near 18 km. The upward looking lidar aboard the DC-8 observed more than a 50% decrease in O_3 at 77 to 90 degrees south between 14 and 19 km, during September, but no discernible trend between 12 and 14 km.

There was also evidence from the lidar data of a decrease in O_3 up to 23 km. The in-situ ER-2 instruments observed changes consistent with this picture.

The TOMS data showed that ozone did not simply change monotonically with time, but in some instances changed dramatically over large spatial scales in the matter of only a day or so. One example of such a rapid change in ozone is demonstrated by the TOMS data for September 4-6 over the Palmer Peninsula and Weddell Sea. Changes of greater than 25 Dobson units (DU) in one day were observed over large regions (3 million square km). The ozone sonde data from Halley Bay and the DC-8 lidar data showed that, during this event, the ozone was depleted over a wide altitude range, from about 14 to 23 km.

2) Does the evidence indicate that both chemical and meteorological processes are responsible for the ozone hole?

The weight of observational evidence strongly suggests that both chemical and meteorological mechanisms perturbed the ozone. Additionally, it is clear that meteorology sets up the special conditions required for the perturbed chemistry.

3) Was the chemical composition of the Antarctic stratosphere observed to be perturbed?

Yes. It is quite evident that the chemical composition of the Antarctic stratosphere is highly perturbed compared to predictions based on currently accepted chemical and dynamical theories. The present findings are consistent with the observations made last year from McMurdo. The distribution of chlorine species is significantly different from that observed at mid-latitudes, as is the abundance and distribution of nitrogen species. The amount of total water within some regions of the vortex is significantly lower than anticipated.

Since late August the abundance of the chlorine monoxide radical within the polar chemically perturbed region has been elevated by a factor of more than 100 relative to that measured at mid-latitudes at the highest altitude at which the ER-2 was flown, about 18.5 km. However, the abundance of ClO was observed to decrease rapidly towards lower altitudes. At the highest flight levels, the abundance of ClO at local solar noon ranged between 0.5 and 1 ppbv for the last month of the campaign. While we have no data at higher altitudes, the observed increase in the abundance of ClO from lower altitudes, coupled with the observed low column abundances of HCl, suggests that the ClO abundance may increase somewhat at altitudes above 18 km. In addition to the steep decrease in ClO abundance at lower altitude, the abundance of ClO was also observed to decrease dramatically outside of the chemically perturbed region.

Chlorine dioxide, OClO, which is most likely formed in a reaction sequence involving the ClO radical, was observed both day and night at highly elevated concentrations compared to those at mid-latitude. The preliminary analyses of these observations are consistent with measurements made from McMurdo last year. The column content of hydrochloric acid, HCl, which is one of the major chlorine reservoirs at mid-latitudes, is very low within the chemically perturbed region reaching column contents below 1×10^{15} molecules per cm^2. In addition, the column amount ratio of HCl/HF within the chemically perturbed region decreased significantly from a normal mid-latitude value of 4 to a value less than unity. While chlorine nitrate was observed, the data have yet to be fully analyzed thus precluding a statement at this time about its abundance.

The bromine monoxide radical has been observed at concentrations of a few pptv within the chemically perturbed region of the vortex at the flight levels of the ER-2. The abundance of BrO decreases at lower altitudes. However, because the observed concentrations are close to the detection limit of the instrument, little more can be said about the altitude dependence. The low measured abundances of BrO, coupled with our current lack of understanding of the ClO + BrO reaction means that we cannot currently assess the significance of this mechanism for ozone reductions at the ER-2 flight levels.

The ER-2 observations of the abundance of odd nitrogen, which is the sum of all nitrogen-containing reservoir and radical species, show, like total water, very low values within the chemically perturbed region of the vortex , indicating that the atmosphere has been denitrified, as well as dehydrated. Abundances of NO_y of 8-12 ppbv were observed outside the chemically perturbed region, while abundances of 0.5 to 4 ppbv were observed inside the chemically perturbed region. A similar large change was observed for one of the nitrogen components, i.e. nitric oxide, NO. In addition, some of the NO_y observations suggest that NO_y component species are incorporated into polar stratospheric cloud (PSC) particles and nitrate was observed in the particle phase on some of the filter samples and on some of the wire impactor samples taken in the chemically perturbed region of the vortex. The column measurements of nitric oxide, nitrogen dioxide, and nitric acid made from the DC-8 exhibit a strong decrease in the abundance of these species towards the center of the vortex. These low values of nitrogen species are contrary to all theories requiring elevated levels of nitrogen oxides, such as the the proposed solar cycle theory.

4) How do the observed elevated ClO abundances support a chemical role in the formation of the ozone hole?

There is no longer debate as to whether ClO exists within the chemically perturbed region near 18 km at abundances sufficient to destroy ozone if our current understanding of the chlorine-ozone catalytic cycle is correct. The rate of decrease in ozone during the month of September at the highest altitudes at which the ER-2 was operated during this campaign is consistent with simultaneously observed concentrations of ClO. However, our present understanding of key chemical reaction rates and photodissociation products within the catalytic process is incomplete. Thus, laboratory studies are urgently needed. It is essential to define the rate of ClO dimer (Cl_2O_2) formation and the photolysis products of dimer decomposition because only one of several possible routes leads to ozone destruction. Once the results of ongoing laboratory studies become available, these in-situ ClO data will allow the chemical mechanism to be quantitatively defined and its consequences better understood.

There is another line of observational evidence consistent with ozone destruction by chlorine catalysis. In the month of August, a consistent positive correlation between ClO and O_3 was observed. By the middle of September, as the ozone concentration was dropping at ER-2 altitudes, a strong anti-correlation developed between ClO and O_3. The anti-correlation was usually present on both large and small scales within the chemically perturbed region.

There are observations that are not entirely consistent with these chemical arguments. For example, based on preliminary data from this year and data from last year from McMurdo, the observed diurnal behavior of OClO, is difficult to rationalize with the present chemical mechanisms, particularly in light of the new observations that the abundances of BrO are low at ER-2 flight altitudes.

5) Can the elevated abundances of ClO inside the chemically perturbed region of the vortex be explained?

Significant progress was made. Observational data that air within the chemically perturbed region of the vortex is dehydrated and that the NO_y abundances are very low are consistent with theories that have been invoked whereby the chlorine reservoir species, $ClONO_2$ and HCl, can react on the surfaces of polar stratospheric clouds to enhance the abundance of active chlorine species, i.e. ClO. The observations also support the picture that the abundance of NO_y is low because odd nitrogen can be removed from the atmosphere by being tied up in ice crystals, which can then gravitationally settle to much lower altitudes. Low abundances of NO_y are needed to prevent the rapid reconversion of ClO to $ClONO_2$. This picture is further supported by the observations of low column abundances of HCl, by occasional observations of high levels of nitrate found in the ice particles, and by the visual and lidar observations of high cirrus and polar stratospheric clouds.

One observation which is currently difficult to understand is the sharp decrease in the abundance of ClO at lower altitudes. This could be due to a lack of understanding of either the abundance or partitioning of ClO_y, or to dynamical effects. Lack of observations of reactive hydrogen containing radicals, hydroxyl (OH) and hydroperoxy (HO_2) currently prevents an assessment of their role in the conversion of chlorine reservoir species to ClO.

6) How do the observations support a meteorological role in the formation of the ozone hole?

There were instances of rapid large scale changes in total ozone where meteorology appears to have been the controlling factor. One such event occurred over the Palmer Peninsula on September 5. Over a period of 24 hours total ozone as observed by TOMS decreased by 25 DU to below 200 DU over an area of about 3 million square km. Such a rapid decrease is difficult to explain chemically. The origin of that air is not known. It could be either air naturally low in ozone, tropospheric/lower stratospheric, or air in which ozone had been chemically depleted. The feature moved over the Weddell Sea and persisted until September 16, when it merged with two other regions of low total ozone. Lidar measurements from the DC-8 showed low ozone values and extensive aerosol layers between 14 and 19 km in the region of the TOMS minimum of ozone. This and other similar events evident in the TOMS ozone data and the SAM II PSC data between September 5 and 14 were spatially correlated with deepening surface pressure lows with marked meridional flow from middle to high latitudes at lower stratospheric levels. The detailed meteorological mechanism by which the surface lows produce the low column ozone remains unclear and further analysis is required.

The data offer no support for sustained large scale upwelling. In the restricted region covered by the ER-2, 54 to 72 degrees south latitude and from altitudes of 12.5 to 18.5 km, measurements of CFC-11 and N_2O which act as tracers of air motions show no evidence of a general increase in abundances above about 14 km during the mission, although there were instances of structure and elevated values.

The meteorology must play a role in the dehydration and denitrification processes. It is crucial to understand whether the necessary low temperatures are maintained radiatively or by ascent, or some combination of both.

7) Does the complexity of the situation suggest that we need to understand the interplay between meteorology and chemistry?

Yes. It is clear from our ER-2 flights that the region of dehydrated and denitrified air maintained a sharply defined latitude gradient throughout most of the campaign. On a purely meteorological definition, the vortex edge would be well outside the dehydrated, denitrified region. The meteorological flow must therefore have been such as to maintain a kind of "containment vessel", in which the perturbed chemistry could proceed without being influenced by mixing in more normal stratospheric air from outside or below.

Very low values of CFC-11, CFC-12, CH_3CCl_3, and N_2O were observed at the upper levels of the ER-2 flight track within the "containment vessel". A key question is how these low values are produced and maintained in the chemically perturbed region.

The concept of mixing at the region of sharp latitudinal gradient is important, since it has the potential to supply nitrogen oxides which would tend to decelerate the chlorine chemistry. The meteorology is thus important in the termination phase as well as in the initiation phase.

8) Can we quantitatively separate the contributions of chemistry and meteorology to the formation of the ozone hole?

No. The September 5 event illustrates the complexity of the ozone hole, and the difficulty of deriving unambiguous dynamical or chemical signatures. The magnitude and rapidity of the decrease are difficult to ascribe to a chemical cause. Air of low ozone content appears to have been transported into the region. The origin of that air is not known. It could be either air naturally low in ozone, tropospheric/lower stratospheric, or air in which ozone had been chemically depleted.

Another illustration of the difficulty of clearly establishing chemical or dynamical mechanisms is the decreasing trends in ozone in regions of low ClO outside of the vortex whose magnitudes are comparable to those within the vortex. This is evident from an examination of the ozonesonde data from the Palmer station at 64 °S and comparing it to the Halley Bay data at 78 °S, and the DC-8 lidar data. In addition, downward trends of ozone were observed in the lower altitude region where ClO concentrations were substantially lower than at 18 km.

9) What are the global implications of the Antarctic ozone hole?

Until we better understand the cause or causes of the spring-time Antarctic hole, we will not be able to address this key question in a responsible manner. Thus, at this time, it is premature for us to speculate on this important topic. However, as we continue to analyze the data that we have acquired and further test and expand the pictures that we have developed, we will be in a better position to address this important question.

10) When will the data be in a form suitable for use in formulating national and international regulatory policies?

As noted in the opening paragraph, the schedule for the assimilation and publication of the results is brisk. Peer reviewed publications will appear in 1988. The results from the 1987 ground-based McMurdo campaign will likely appear on about the same schedule. Both sets of these completed conclusions would be the best basis for any possible policy re-evaluations. The major international scientific review scheduled for 1989, which will serve as input to the 1990 policy review of the Montreal Protocol, will have these conclusions available.

STATEMENT OF SENATOR GEORGE MITCHELL

Before the First North American Conference on Preparing for Climate Change: A Cooperative Approach
October 29, 1987

I am pleased to be with you today, and to join my colleague Senator Chafee as Honorary Co-chairmen for the First North American Conference on Preparing for Climate Change. I congratulate the Board of Directors of the recently created Climate Institute and the co-sponsors of the conference. You have arranged a challenging agenda and assembled an impressive panel of expert speakers on the climate change issue.

The breadth and diversity of subjects you are discussing is revealing. They give a clear indication of the complexity and seriousness of the global warming problem.

Your agenda raises basic questions about planet Earth as we now know it--in terms of the physical characteristics, the ecology and even the economic balance that sustains human society.

Obviously, we are discussing potentially dramatic impacts. These are very challenging problems for the scientific and technical community. There is a need to define and understand the nature of the impacts from global warming. There is a need to predict the timing, the magnitude, and the extent of the changes. There is a need to identify and assess alternative strategies to correct or adapt to the changes.

I want to impress upon you that these issues are even <u>more</u> challenging problems for the policymakers. The scientists cannot give us as much guidance as we really need to form and justify our policy options. These are not issues where a "quick fix" solution is available. There are no ready or easy regulatory alternatives, nor would a simple infusion of dollars provide enough answers.

Yet, the impacts of climate change are of such consequence that we cannot afford to wait for all the questions to be answered with certainty.

A prime example of the risks of waiting is the atmospheric "surprise" presented by the Antarctic "ozone hole." We have been aware of the suspected threat of ozone depletion from chlorofluorocarbons since 1974. Now we are witnessing a fifty percent loss of ozone each year over Antarctica from the chlorine man has added to Earth's atmosphere. A disruption of that extent was not predicted by any scientific theories. We heard at a Senate Subcommittee hearing this past Tuesday that the Antarctic ozone hole is with us for at least one hundred years even if we stopped adding chlorofluorocarbons to the atmosphere tomorrow.

This past January, Sen. Max Baucus and I co-chaired a joint Subcommittee hearing on the issues of global warming. The testimony of expert witnesses left no doubt about the validity of the greenhouse theory and the certain change it will bring.

Dr. Ramanathan of the University of Chicago testified that we are already committed to a global warming of up to two degrees Celsius from the increased gases added to the atmosphere since the beginning of the industrial era in about 1850. In other words, even if action were taken tomorrow to limit emissions of these gases, we have already set in motion a significant temperature and climate change.

It has been 8,000 years since the Earth has been one degree Celsius warmer than now and 70 million years since the average global temperature was five degrees Celsius warmer than today.

Dr. Thomas Wigley from the University of East Anglia testified that the Earth has warmed one degree Fahrenheit in the past one hundred years. Recently, the warming trend has been very rapid. Dr. Wigley believes this warming is the first signal of the greenhouse effect.

Dr. Wallace Broecker of Columbia University testified that climate change may occur suddenly and the magnitude would be unpredictable, thereby limiting our ability to cope and adapt.

I hope you will address some of the remaining major questions related to climate change.

- What is the role of the oceans and their circulation patterns in global warming?
- Could the oceans be absorbing much of the increased carbon dioxide and producing a lag-time effect on actual temperature increases?
- What is the role of clouds and cloud formation in temperature and climate?

- What kind of predictions can we make about climate changes for specific regions of the globe?
- What are the biotic feedbacks, how well can plant and animal species adapt?
- What are the sources and sinks of methane, and what are the risks of releasing this greenhouse gas from under the Arctic permafrost?
- What are the processes that govern the formation of sea ice?

This is only a partial list of the unanswered technical questions. We were reminded in Tuesday's hearing on Antarctic ozone depletion of the urgent need to better understand the total Earth system and its interrelationships. Dr. Michael McElroy of Harvard University proposed the following scenario: increased ultraviolet radiation from stratospheric ozone depletion over the Antarctic may be causing damage to the marine life at the bottom of the food web; this phytoplankton in the oceans absorbs carbon dioxide. If marine productivity is hampered, the oceans may begin to release carbon dioxide, contributing to global warming; and the capacity of the oceans to add carbon dioxide to the atmosphere has been calculated at six times the level at which man's activities are increasing carbon dioxide.

It is clear that the greenhouse effect and climate change are real concerns for the condition of this planet within our lifetimes. It also is clear, as Dr. Ramanathan stated at our January hearing, that there is a significant gap between our scientific ability to understand the system and predict the likely changes, and our technological capability to pollute the atmosphere.

The problem of addressing global climate change is compounded by its interrelationship to other major policy areas, including air pollution, energy conservation, and energy use and pricing policy in general. And of course, this is an international problem, with environmental, economic and even national security ramifications.

We are behind in our efforts to begin policy analysis and development to respond to the threat of global climate change. In the next few weeks I will be joining my colleagues, Senators Baucus and Mr. Chafee, to introduce a resolution in the Senate calling for international negotiations on global warming. The resolution will state that it is the policy of the United States to urge that we begin international negotiations within two years, at the time of the next United Nations Environment Programme Governing Council session, scheduled for July of 1989. The goal of these negotiations should be stabilizing the level of greenhouse gases in the atmosphere.

The key elements of success in dealing with an unprecedented environmental problem of this nature are cooperation and commitment. The stakes are so large that we must have full support and strong leadership, on an international basis, from the business and financial community, scientists, environmentalists, and government at all levels, including the Congress. That is the only way we can meet the challenge of global climate change.

CLIMATE CHANGE: A VIEW FROM CONGRESS

Remarks by

Congressman George E. Brown, Jr.

To The First North American Conference on
Preparing for Climate Change: A Cooperative Approach
Washington, DC
October 29, 1987

Those of us studying the global climate change problem over the years have witnessed many great achievements and experienced many frustrations. The scientific community can be very proud of its many achievements, such as improvements in monitoring techniques, spaceborn instrumentation, and high-speed computers that allow the global synthesis of information at an unprecedented scale. The frustrations, as well as the challenges, lie mainly in the many uncertainties remaining in our understanding of our ever-changing atmosphere, geosphere, and biosphere. Frustration can also be found in the difficult task of maintaining adequate funding for climate research.

While we have made significant progress in understanding the science of global climate change, it is time for us to recognize that much less progress has been made in the area of policy analysis and application. This shortcoming in our overall approach to the climate change problem is accentuated by a notion that is becoming increasingly clear: the costs of waiting for scientific certainty to take action could simply be too great. The possibility of facing catastrophes such as drought, famine, or a rising sea level is frightening. Indeed, a strong case can be made in favor of acting now, given that we can identify economically and politically sensible steps. The CFC agreement in Montreal is a shining example of what can be accomplished. Of course, any preventative response we undertake must be conducted in parallel with continued intensive research and the development of strategies for adapting to a climate change.

I would like to go back to 1978, the year the National Climate Program Act was enacted. The purpose of this Act was to establish a process for coordinating climate research, monitoring, prediction, and information dissemination among various federal agencies. It was meant to be an experimental prototype for the organization of research that crosses agency and disciplinary boundaries. The authors of the Act were far sighted, indeed, in stating that it should "include in its scope the possibility of informed, intelligent action in response to climate change, as opposed to more passive adaptation to climate." In addition, the Conferees specifically endorsed a basic concept in the Senate bill, that the "research program should include activities to improve the understanding of the social, economic, and political impacts of climate change."

These policy-oriented aspects of the National Climate Program Act alert us to recognize the interdisciplinary nature of the climate change problem. Effective and sensible policy responses, such as increased energy conservation, are predicated on effective communication between scientists, economists, social scientists and policymakers. Scientific research, we should realize, in this case is no better than scientists' ability to communicate their findings to those who can implement appropriate policies and programs to respond effectively to scientific information. Those of us in all the various professions, as well as in the various agencies and countries, must continue to communicate, cooperate and respond in unison.

Despite our failure to achieve full success in implementing the policy-related mandates of the National Climate Program Act, we are much farther along in our abilities to monitor, assess, and thus respond to climate change issues. And we can learn a great deal from experience gained since the Act was passed. In pursuing cooperative agreements between nations and fostering international cooperation and coordination, we can use the National Climate Program Act as a model. Achieving cooperation among nations, after all, can't be that much more difficult than achieving cooperation among U.S. government agencies!

The discussions so far at this conference have focused on the changing physical climate of the atmosphere, but there is another climate you should concern yourselves with if your scientific findings are to have an impact commensurate with the scope of world climate change. Notably, I am thinking of changes in the economic and political climate. Thus, in my remarks I want to talk about the stock mark crash, a subject which seems far removed from the topic at hand, but which actually has a profound connection to your deliberations. In this context, I hope that your panel on Societal Planning had more of an opportunity to discuss the link between financial institutions, capital investment and climate change. However, I understand that future Climate Institute meetings will examine the likely impact of climate change on municipal infrastructure and private sector investment decisions. These areas are very important--perhaps even the crucial elements--in our response to long-term economic challenges, be they the challenge of responding to changing physical climate or that of maintaining economic competitiveness in international markets.

Policies on capital investment affect the flow of trillions of dollars annually and define the general character of an economy from education to energy use for 30 to 50 years. Capital investment is our lever on the future over the time period of concern to you.

So what about the relationship between the stock market and the greenhouse effect? First, where does global climate warming fit, in relation to the other events that buffet policymakers? It has been crudely estimated that the costs of a warmer climate associated with doubled carbon dioxide levels might amount to three percent of the Gross World Product, or about $500 billion annually. This is a staggering sum, and the costs will be felt by millions of people. However, consider that in the last two months, the New York Stock Exchange alone lost $1 trillion in value, and pension plan assets upon which our elderly depend declined by nearly $200 billion. Congress grapples daily with how to stabilize capital markets and protect national investments. In light of this, it should not surprise you when Congress turns a deaf ear to your pleas that it act to avert the devastating effects of climate change 30 years from now. To overcome this, you must ally yourselves with those concerned with other sometimes drastically changing climates in the political and economic areas.

There is, however, another more important lesson to be drawn from the stock market crash. It concerns the timing of scientific advice in order to maximize its impact on policies. Political and economic leadership often require that one must act when a society is ready to move, even when one does not have perfect information about the future. The scientific community must learn this lesson if it hopes to effect momentous policies on global energy use.

Congress is often criticized for reacting only to crises. But there are times when, in the course of meeting an immediate crisis, that the resulting policies set the political and economic stage for generations to come. Fifty years ago, Franklin Roosevelt and the Congress were trying to meet the immediate problem of putting people back to work and providing a modicum of income security. They established Social Security, Unemployment Compensation, the Securities and Exchange Commission, government-sponsorship of research and development and Keynesian economic policies that provided the background for our economic growth from 1932 to the present day.

The recent crash indicates to me that the U.S. has once again entered one of those pivotal periods in history, when what we do today will endure through our children's lives and well into the period when climate warming will become significant.

Let me give you an example. In order to stabilize our capital markets from panics, and to increase savings for long-term investment in education and innovative technology, I shall shortly introduce legislation to create a National Retirement Account Bank, with many of the powers now possessed by the Federal Reserve System. The bank will be capitalized by surpluses in Social Security trust funds, that will eventually amount to $13 trillion. Currently, these surpluses can only be invested in Treasury bonds to reduce the apparent federal deficit. Under my plan, the surpluses would be invested throughout the economy in both public and private securities in ways to improve our international competitiveness. In times of panic or excessive speculation, the Bank could buy or sell securities so as to moderate financial gyrations, just as the Federal Reserve now protects banks from runs on deposits. If these investments earn an 8.5% return, then computer simulations conducted by my staff indicate that we could one day repeal Social Security taxes.

My point to you here today is that if Congress establishes such a bank, then the scientific community must help to ensure that its investments take into account long-term environmental changes such as global warming.

How might scientific input to economic policy occur? Right now there is virtually no coordination between science and technology policy, and economic policy, even though the new Nobel laureate, Robert Solow, estimates that technological innovation has been the largest, single contributor to economic growth over the last century. To rectify this situation, I shall shortly introduce legislation that would, among other things:

(1) establish a cabinet-level Department of Science and Technology;

(2) require that at least some members of the Council of Economic Advisors and the Boards of Governors of the Federal Reserve banks, have scientific and technical backgrounds; and

(3) require that the Federal Reserve Board consider investment in science and technology when making decisions on interest rates and money supplies.

These are but a few suggestions. I strongly urge you to get involved in these issues even though they seem far-removed from your normal concerns. After all, scientists must be public citizens, too. In so doing, you will have an input to the investment of billions or even trillions of dollars. If you do not become involved in this way, then momentous decisions by economic institutions will be made without any consideration for your concerns. The time for you to act is now, because I believe it is within the next few years that Congress will set up institutions like these to address our economic problems for many years to come.

One final note: The recently concluded Montreal agreement on stratospheric ozone is an enormously hopeful step in global cooperation on a serious environmental problem. Because of the inertia of capital investment in energy and agriculture, to address the global warming problem with any success, we must act long before a warming is observed with certainty. Therefore, I believe the time has come to use the Vienna-Montreal process as a model for addressing other related climate change issues.

I intend, in the near future, to join with other members to introduce in the House a resolution calling for an international convention, similar to the one in Vienna, to begin negotiations in two years for reducing greenhouse gas emissions, and mitigating global climate change. As you can gather from my remarks on the importance of economic policy, I hope that such a convention would consider economic development and investment policies, in addition to setting emissions targets. In introducing this resolution, we would hope to work closely with our colleagues, Senators Baucus, Chafee, Mitchell, and Stafford, who I understand are planning to introduce a similar resolution in the Senate. I would also expect and welcome the collaboration of two of my colleagues here today, Claudine Schneider, and Bill Green, with whom I have worked closely in the past. Thank you.

SPACE PRIORITY: EARTH

Comments of Congressman Bill Green

It is my intention as ranking Republican of the House Appropriations Subcommittee with responsibility over NASA, to attempt to make earth science a U.S. space program priority.

I am now seeking the support of other Members of Congress in the House and Senate to direct NASA to emphasize science projects even if it requires holding down spending for the planned Space Station.

As my Subcommittee also oversees funding for the federal Environmental Protection Agency, the Council on Environmental Quality and the National Science Foundation, and as I am now in my second term as co-chairman of the Environmental and Energy Study Conference in Congress, I have been sensitized to environmental issues. For some years I have been working on acid rain proposals, for example, and examining research into the greenhouse effect and the Antarctic ozone phenomenon.

Thus, as a conferee in the House-Senate negotiations on the FY 88 appropriations for NASA, I will recommend report language stipulating that:

a. NASA continue allocating approximately 20% of its budget for science programs, and
b. The Station itself should be reduced in scope and size in the event of budgetary cutbacks, if that is necessary to maintain funding for science projects, and
c. The earth study program that former Astronaut Dr. Sally Ride termed "Mission to Planet Earth" should be given funding priority in coming years.

While I would like to see NASA able to "do it all" in terms of manned and unmanned space missions, given the fiscal realities, it will be impossible to fund simultaneously all programs, including manned and unmanned Station operations, independent science satellites, Moon colonies and trips to Mars. The "Mission to Planet Earth" earth science program has special immediacy.

"Mission" is envisioned as a multi-national project with space platforms used to study global cloud, vegetation and ice cover; rainfall and moisture; ocean chlorophyll content and topography; motions and deformation of tectonic plates; and atmospheric concentration of gases such as carbon dioxide, methane and ozone. Most of the earth science work would be done from independent satellites.

Concerns about ozone depletion, global warming, loss of tropical rain forests and damage to the oceans demand greater information gathering, and with the aid of space satellites, we can obtain more knowledge of the Earth's worldwide environment, from rainfall patterns to pollution drift. Mission to Planet Earth should have the highest priority so that we can develop essential data as to precisely what is happening to our environment.

While the main Space Station is to have scientific value, the recent National Research Council report warned that the Station's planned orbit was not appropriate for most earth studies. In fact, most earth science work is to be done from independently-launched polar-orbit satellites or geosynchronous orbits rather than from the Station. It is my intent to encourage development of such independent operations.

(Under current schedules, the U.S. is scheduled to launch an earth science platform in 1995 with additional environmentally-oriented satellites launched into polar orbits by the Japanese and Europeans a few years later. The "Mission" plan also calls for four geosynchronous platforms for earth study.)

Chemical Alteration of the Atmosphere

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October 28, 1987
Washington, D.C.

I would first like to convey to you the best wishes of my Minister, the Honourable Tom McMillan. He regrets that he cannot be with you today.

On his behalf, I would like to share a few thoughts with you about the chemical alteration of the atmosphere. While the title of your conference is "Preparing for Climate Change", I'm pleased to see that you've scheduled a Panel Discussion entitled "Global Warming, Stratospheric Modification, Ground Level Ozone and Acid Rain: How Will Their Interaction Affect Air Quality?"

These problems are indeed interconnected. A stressed ecosystem responds to the net effect of these and other environmental factors. The design of environmental monitoring and research programs, and the control actions we take, must increasingly recognize this fact. The time has come to increase the number of comprehensive multi-media monitoring sites to provide a better data base for interdisciplinary research. The meteorological observations at such sites must include atmospheric chemistry. Increasingly, the definition of climate will have to include both the physics and the chemistry of the atmosphere.

Canada has taken a few steps in the right direction. About a year ago, I had the pleasure of opening a new air pollution monitoring station and laboratory at Alert, 82°N. Air chemistry observations there are now supplementing the valuable longer-term record of conventional meteorological observations.

A certain historical complacency about air pollution problems is perhaps understandable. Man started to pollute the air when he learned to make fire. Primitive peoples, at least in middle and high latitudes, had to contend with the smoke from cooking fires in their dwellings and villages. The growth of cities saw the emergence of urban pollution and the imposition of simple, if sometimes selective and intermittent, controls. In the 1600's, at least one British government prohibited coal-burning in London when Parliament was in session. One can only speculate that there were probably few winter-time sessions of Parliament - or perhaps they compensated with heated debates!

The Industrial Revolution exacerbated air pollution problems in the sooty cities and the surrounding countrysides. An English scientist of the era, Robert Smith, first coined the term "acid rain" in a book called "Air and Rain, the Beginnings of a Chemical Climatology", in 1872.

Near the end of the last century, the Swedish scientist, Arrhenius, expressed concerns about the potential impact on climate of the increased atmospheric concentrations of CO_2. He, like Robert Smith before him, received little recognition for his prophetic genius.

Here in North America, the first noteworthy dispute over regional transboundary air pollution was the Trail Smelter case in the 1920's. Farmers in the State of Washington attributed crop damage to sulphur dioxide emissions from a zinc smelter in Trail, British Columbia. The problem was eventually resolved in 1941 by a bilateral arbitration tribunal which established principles for transboundary air pollution parallel to the U.S./Canada Boundary Waters Treaty of 1909.

Those general principles affirm that a country should not export its pollution to the extent that it causes serious harmful effects to health, property or the environment in neighbouring countries. These principles have been more recently reaffirmed in the 1972 Stockholm Declaration on the Human Environment, the 1972 and 1978 Great Lakes Water Quality Agreement, the 1979 ECE Convention on Long Range Transboundary Air Pollution, the 1980 Memorandum of Intent between Canada and the United States Concerning Transboundary Air Pollution, and the recently signed U.S./Mexico Agreement on transboundary air pollution.

In spite of the very long history of the urban air pollution problem in many parts of the world, it was not deemed serious enough to be addressed by regulatory law until the middle of this century. In 1947, California became the first U.S. state to pass air pollution legislation. The first U.S. federal air pollution law was passed in 1955. In Britain the great London smog of 1952, which resulted in hundreds of deaths, led to the passage of a federal Clean Air Act in 1956.

As is the case with most social and environmental reform, the early proposals for air pollution regulation were met in some circles first with derision and subsequently with strongly-organized opposition. There were claims that such legislation was premature and oppressive, based on inadequate and inconclusive research, and even somehow un-British or un-American in threatening industrial viability or competitiveness. Nevertheless, the record demonstrates what I would call a "sort of a success story". While the picture is not universally bright, we in North America can be proud of the general improvement in air quality in our cities over the last few decades. Private enterprise is adapting. The technological fix has proven itself once again. Industrial innovation in the United States and elsewhere has led to more efficiency, economy, and effectiveness in air pollution controls. Industries are now considering intrinsically clean processes rather than "add-on" technology.

I call this "a sort of a success" because that legislation, designed to address the air pollution problems of the fifties, did not foresee, and was not designed to combat, the more recent problems of regional and global air pollution, which require different control criteria. Our conventional domestic legislation focuses on ambient air pollution concentrations near the emission sources, and on the protection of human health from short-term exposures to high concentrations of pollutants. Current legislation has been demonstrably effective in meeting this primary objective. Today's more complex and widespread issues of atmospheric pollution, however, demand correspondingly more complete legislation.

Our ingenuity in meeting the requirements to reduce near-source concentrations of air pollutants proved to be short-sighted. In our collective wisdom we decided that one solution to pollution was dilution. Taller stacks were the answer. We North Americans happily embraced this idea. The result was that while diluting the pollution, we spread it over increasingly larger regions.

It is true that what goes up usually comes down, in some form, somewhere. And what comes down now includes things like acid rain, whose cumulative adverse impacts on many of our ecosystems over a long period of time are obvious. Combatting these long term regional deposition effects requires not only revamped domestic legislation but also bilateral or multilateral accords. The 1979 ECE Convention on Long Range Transboundary Air Pollution led to the Helsinki protocol of 1985, when Canada and twenty other nations agreed to a thirty per cent reduction in annual sulphur dioxide emissions by 1993 at the latest.

Canada has gone further. We determined that moderately sensitive aquatic ecosystems require a limit on depositions of wet sulphate of no more than eighteen pounds per acre per year. To achieve this figure requires a reduction in allowable emissions of sulphur dioxide from sources in eastern Canada of about fifty percent based on 1980 allowable levels, together with about a fifty percent reduction in the flow of sulphur dioxide from the U.S. into Eastern Canada. Canada is committed to achieving its reduction by 1994. Of the seven Canadian provinces affected, the federal government has signed agreements with six, and is negotiating an agreement with the seventh, to meet this target.

But, as everyone who reads the National Geographic, Time Magazine, or the daily newspapers knows, our serious problems don't end with the regional transboundary ones.

Even though Arrhenius raised the problem of CO_2 and climate change almost a century ago, there was little concern in most quarters until the 1950's. In response to a growing interest among scientists, the United States commenced long-term continuous monitoring of CO_2 at Mauna Loa. That pioneering work eventually quantified the clear upward trend of global CO_2 concentrations. Meanwhile, improvements in computer technology were allowing scientists to develop more complex and sophisticated models to assess the probable impacts on climate of an enhanced Greenhouse Effect. Growing concerns about the problems of climate variability and change, and their social and economic impacts, led the World Meteorological Organization to convene a First World Climate Conference, in Geneva, in 1978. This resulted in the establishment of the World Climate Programme, led by WMO and co-sponsored by UNEP and ICSU, in 1979. The World Climate Programme has generated an acceleration in research on climate, climate change and its socio-economic impacts, but much more needs to be done. WMO is now planning a Second World Climate Conference in 1990.

The projections of climate warming produced by current General Circulation Models (GCM) are familiar to all of us. The public is gradually becoming aware that a strong scientific consensus has emerged, in spite of the fact that the media tended, in the recent past, to give "equal time" to the minority forecasters of long-term climate cooling. That well-intended media penchant for debate and controversy convinced average citizens that the climate change experts were just as confused as the public.

Perhaps we need better ways of conveying authoritative scientific consensus to decision-makers, and through the media to the public, in a timely fashion.

As most people now realize, there is a reasonable agreement among the various GCM Model outputs with respect to Global average temperature increases for a doubled-CO_2 world. A key point concerning these climate projections is that the rate of warming is likely to surpass anything experienced in human history. We all recognize that our societies are resilient and adaptable. But can we in this case rely on a last-minute "technological fix" to mitigate or adapt to global environmental change beyond the limits of human experience? To do so would be very unwise. I am convinced that what we will eventually need to deal with this problem is a global "Law of the Atmosphere". It is not premature to begin considering the options available to us in that context.

A first step toward such an accord has already been taken to deal with the specific problem of stratospheric ozone depletion. Just six weeks ago, twenty-four countries signed the Montreal Protocol on Substances that Deplete the Ozone Layer. In doing so, they remarkably set aside the narrow definitions of national interests that have traditionally shaped international environmental debates. I am happy to note that Canada and the United States played leading roles in the development of that historic protocol.

Given the century-old awareness of acid rain and the CO_2-Climate Change problem, the length of time between problem recognition and international control action was comparatively short in the case of the stratospheric ozone layer.

One of the first major perceived threats to the ozone layer was associated with the development of stratospheric airliners. In a 1975 report, the U.S. National Academy of Sciences pinpointed, as a cause for concern, the projected high-level aircraft emissions of oxides of nitrogen and sulphur, first because of their potential for destroying stratospheric ozone, and secondly for their formation of stratospheric aerosols that could result in changes in surface climate! These pollutants, needless to say, are also the familiar culprits in the acid rain problem.

While the threat of fleets of commercial stratospheric aircraft didn't materialize, another factor identified by the National Academy of Sciences subsequently became the major concern. The Academy recommended, and I quote, "an immediate quantitative assessment ... of the possibly large stratospheric effects of stable compounds, such as chlorofluoromethanes involved in aerosol spray cans and refrigerants". The rest, as they say, is history. While the story of the stratospheric ozone protocol is a comparatively short one, it still took over a decade from conceptualization to realization. Is it still too early to begin thinking about a broader Law of the Atmosphere?

A side benefit of the Montreal Protocol is that it will have at least a modest influence on slowing down climate change, since CFC's are also Greenhouse Gases. Another linkage that's worth noting is that significant decreases in stratospheric ozone, by permitting more UV-B radiation to reach the earth's surface, will have an impact on photochemical processes that occur there. Because of our concerns with substances such as boundary-layer ozone and NO_x and their adverse effects on surface ecosystems, we need to know more about these complex interactions.

Even seemingly small incremental changes in the chemistry of the atmosphere may be very significant. A favorite argument in some anti-control quarters is that many of the atmospheric chemicals of concern (such as carbon dioxide) occur in nature, in quantities greatly exceeding the man-made components. So - why worry? This argument misses the point. Man-made emissions have become large enough to significantly disturb the natural environmental balance, including the ecosystems that have evolved over centuries. And the impacts are clearly increasing.

How do we cope with the expanded scope of air pollution problems? We can at least rest assured that the recent rapid expansion in the spatial scale of serious impacts has now come to rest at the global scale. We've clearly reached the point where there are no more "tall stack" kinds of solutions. We either have to arrest and reverse the emissions or accept the dismal economic and social consequences of a continued degradation of our environment and natural resources. According to the World Commission on Environment and Development, the only rational answer to the many complex problems of global change is to pursue a course of sustainable development, nationally and internationally. Is this altruistic pie in the sky? The Brundtland Commission doesn't seem to think so, and neither does the Canadian government. A Canadian national task force of high-ranking federal, provincial and industrial representatives made recommendations last month reflecting their recognition that national and international economic progress will depend on a healthy environment. The general idea is that just as poverty is a bad environment, a bad environment is poverty. What is needed is a new social contract between development and environmental conservation. The Brundtland Commission report is not one of gloom and doom, but it does stress the urgency of actions to avoid what might otherwise be a bleak future for all nations.

In June of next year Canada will host an international conference in Toronto called "The Changing Atmosphere: Implications for Global Security". It will provide a forum for discussion of these issues by leading world experts in environmental science and the major economic sectors impacted by global change. Specific actions related to some of the recommendations of the Brundtland Report will be proposed.

All of us attending this conference recognize that among the various aspects of global change, climate change will exert a pervasive and controlling influence. We have a job to do in convincing many of our fellow scientists, our economist colleagues and decision-makers that research on climate change and its impacts demands more attention. The Brundtland Commission defined three "Global Commons" - the oceans, the Antarctic and outer space. Let us go one step further. We must begin to treat our shared atmosphere as a global commons, not only with words, but with actions.

A recent survey of Canadian newspaper coverage provides an indication of how atmospheric pollution is rising in the public consciousness. Of all news stories printed, the percentage of environmental stories increased from four percent in 1978 to seven percent in 1986. Of these environmental stories, the number dealing with atmospheric pollution increased from about seven percent in 1978 to about twenty-one percent in 1986.

Finally, I suggest that redoubled efforts are needed to ensure that consensus scientific results are presented to decision-makers in a totally objective and unbiased manner. It's obvious that actions to protect our health and our environment must be based on careful scientific research. Without such work on stratospheric ozone, for example, culminating in the detection of the Antarctic ozone hole by British and U.S. scientists, the Montreal protocol would not have been achieved. Given the vastness and complexity of our environment, we cannot hope to answer all questions about its interactions, at all levels of detail, with 100 percent certainty. We must seek strong and credible scientific consensus on major problems and not muddle the purely scientific interpretations and conclusions with other policy factors. Political decision-making on environmental controls is widely recognized as a difficult process, which must weigh in the balance our best collective scientific judgement and the separate factors of the costs and risks of action or inaction. Our concerned and informed publics will increasingly demand openness and a clear explanation of these separate factors.

When questionable interpretations of scientific results do occur, we fortunately have Royal Societies and National Academies of Science capable of reviewing all relevant research and producing objective conclusions and recommendations. We should be prepared to rely heavily on the most authoritative, credible and widely-respected of these institutions to avoid misunderstandings and resolve disputes.

During our history, Americans and Canadians have teamed up successfully to tackle many momentous problems in a spirit of mutual concern and respect. This North American Conference is an excellent illustration of the kind of co-operation we need to address the major challenges posed by the increasing chemical alteration of the atmosphere. I congratulate the organizers and wish you all - researchers, managers and decision-makers - success in your important work.

WARMING OF PERMAFROST IN THE ALASKAN ARCTIC

by

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In this note we discuss the use of temperature measurements in deep wells to detect and monitor recent changes in climate. Such measurements show that the surface of permafrost has been warming rapidly throughout much of the Alaskan Arctic during the last century. The cause is unknown. (For a more complete discussion, see Lachenbruch and Marshall, Science, 234, 689 (1986).)

Carefully measured temperatures in deep wells can be used to reconstruct the history of temperature change at the earth's surface during the recent past. The general method has been well known to solid-earth geophysicists since Lord Kelvin used it to estimate the age of the earth over a century ago. However, the method probably has not been exploited as much as it could be in the search for contemporary climatic change, the subject of our panel discussion. For reasons that I shall point out the geothermal method is particularly well-suited to climatic studies in permafrost, and such studies are of considerable interest because of the scarcity of Arctic weather records, and the central role played by the Arctic in global climatic models.

The Alaskan Arctic, a region about the size of the state of Colorado, is shown in Figure 1. The symbols show where we have made earth temperature measurements; for the most part in idle oil-exploration wells. It is a region with few weather records; the longest is at Barrow, and it dates back only 60 years. Although the written climatic record is short and incomplete, a substantial unwritten record is maintained by the earth itself in its long thermal memory. As the surface of the earth warms, the temperature change propagates slowly downward into its interior. If we drill a hole a century later and measure temperatures in it carefully, we should be able to determine the depth to which that temperature signal has penetrated and, in principal, calculate backward from this information to estimate the time and magnitude of the change at the surface. However, the process of drilling the well used for observation causes a large temperature disturbance that takes several drilling periods to dissipate (if the well is drilled in one week, dissipation takes several weeks; if drilling takes a year, dissipation takes several years). Consequently, it is usually necessary to make repeated measurements over a period of years to identify and correct for the drilling disturbance. As these sites were generally wilderness until the drilling started, there are no disturbances from previous human activity, and evidence of previous changes in earth temperature generally indicate a change in climatic conditions.

The profile in Figure 2 illustrates the geothermal signature of changing climate at a typical site (AWU, Figure 1) 150 km inland from the Arctic Ocean; the drilling disturbance has been removed and the points represent natural earth temperatures to within 0.1°C or so. The curve consists of two parts--a deep linear part and an upper anomalous curved part. The linear part represents the steady flow of heat down a constant geothermal gradient (Γ_0)

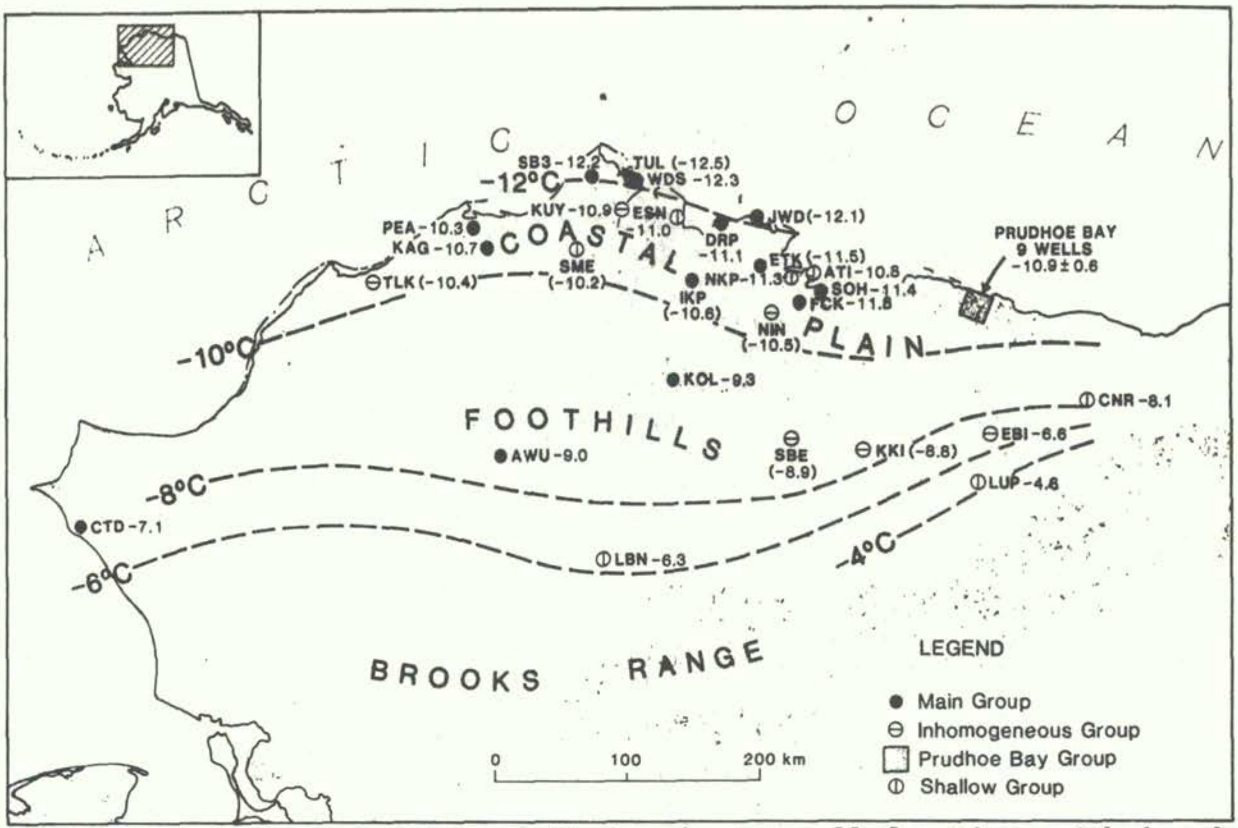
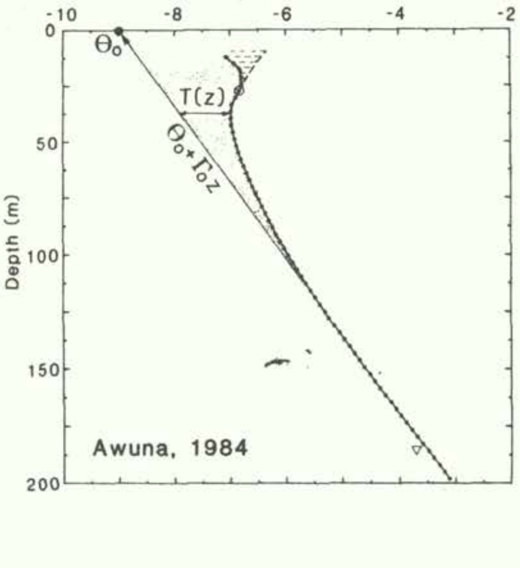


Figure 1. Map of northern Alaska showing well locations with keyed symbols. Dashed contours represent the extrapolated long-term mean annual temperature at the top of permafrost, θ_o.

Figure 2. Measured temperatures (dots) at AWU corrected for drilling disturbance. Line with slope Γ_o and surface intercept θ_o is least-squares fit to the linear portion of profile. T(z) (stippled region) is temperature anomaly caused by recent climatic warming.



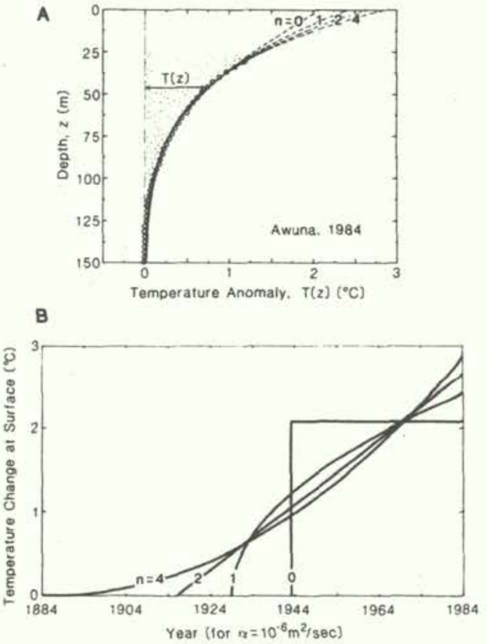


Figure 3. (A) Warming anomaly T(z) obtained from Fig. 2. Circles are observations; curves are best-fitting geotherms calculated for the four forms of temperature history shown in (B).

from the earth's interior; if the climate were stable and the earth homogeneous, the geotherm would follow this linear trend to the surface where it intersects to give the long-term mean value of the surface temperature. The curved portion evidently represents the effect of a recent change in the surface temperature toward warmer values. The little hook in the top 25 m is a very recent cooling effect; probably the surface disturbance from the gravel drilling platform which was emplaced four years before the temperature observations were made. Neglecting this, it is easy to see from Figure 2 that the earth's surface temperature has increased 2° or 3°C (from about -9°C to -6° or -7° C). Trying to figure out when this warming started is a greater challenge than estimating its magnitude, and this is where the bonus for working in permafrost comes in. Most materials near the earth's surface have water flowing through them transporting heat in complicated ways. In permafrost, the ground water is immobilized as ice and heat can travel through it only by conduction, a simple process following well-known mathematical rules.

We can therefore subtract out the geothermal gradient, and calculate what kinds of simple temperature histories could have generated our climatic temperature anomaly ($T(z)$, Figure 3a). Four simple compatible histories are shown in Figure 3b. If the change were a sudden step, it must have started in the 1940's with a jump of a little over 2°. If it were a linear change, it started about 1915 with the present change about 2½°, and if it accelerated with the square of time, it probably started around the turn of the century with a total increase somewhat less than 3°. (The dates are based on an assumed thermal diffusivity, $\alpha \propto 10^{-6}\ m^2/sec$). The calculated anomaly for each of these models is shown in Figure 3a. It is seen that below 25 m they all fit the data within observational error; above 25 m, the data reflect complications associated with surface changes in the last decade incompatible with our simple models. Hence there is no point in trying more refined approximations for the century-scale climatic event. At first sight, this seems to be a disappointingly ambiguous result. On second thought, however, it is seen that all 4 curves give us the same big picture; the permafrost surface temperature at AWU has increased 2° or 3° in the last 40 to 90 years. This is a rather substantial message when one considers that it comes from a wilderness from which no thermal history information was previously available.

This warming results from a net accumulation of heat in the earth at a rate which we can now calculate. Average values are 0.1-0.2 watts per square meter (climate flux "C," Figure 4); the steady geothermal flux flowing in the opposite direction ("g," Figure 4) is about 0.06 W/m^2. It is of interest to compare these gentle solid-earth fluxes to the more vigorous activity on the other side of the earth's surface; the larger "top-side" fluxes drive the ecosystem and their balance point determines the earth's surface temperature. They consist of the incoming and outgoing radiation components and their difference ("net," Figure 4a) which, among other things, is responsible for melting snow and evaporating water allowing them to return to the sea or sky to balance both the thermal and hydrologic budgets and get ready for the next annual cycle. Notice from the numbers on the arrows (Figure 4a) that these top-side climatic fluxes do balance to zero as they should if the climate is not changing. But we just discovered from the solid earth (Figure 3) that climate <u>is</u> changing; in our example 0.16 W/m^2 more is going into the earth than out. As this is just 1/100th of the net radiation (itself a difference of large numbers), we could never detect such a small difference by trying to

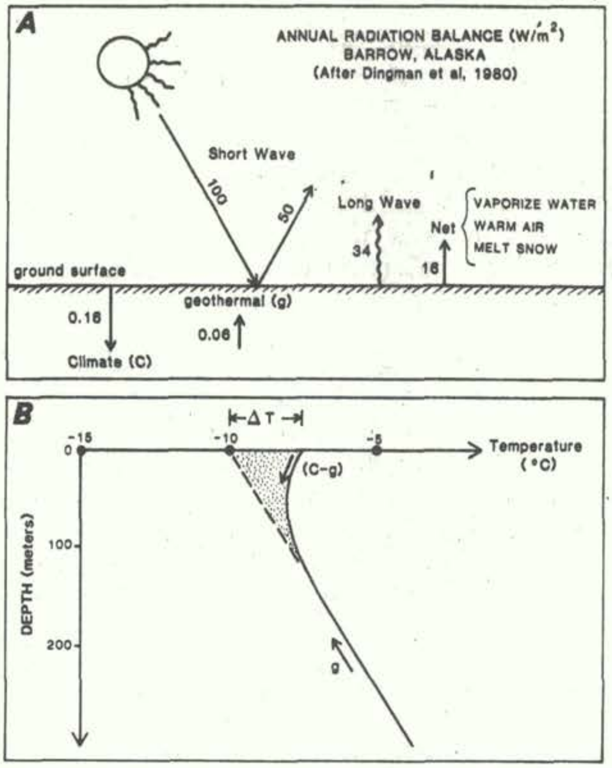


Figure 4. Typical thermal conditions in permafrost regions of the Alaskan Arctic. A. Average annual energy fluxes above and below the earth's surface. B. Geothermal regime: g is steady geothermal heat loss, C is heat gain from warming climate, stippled region represents total heat accumulation from warming event.

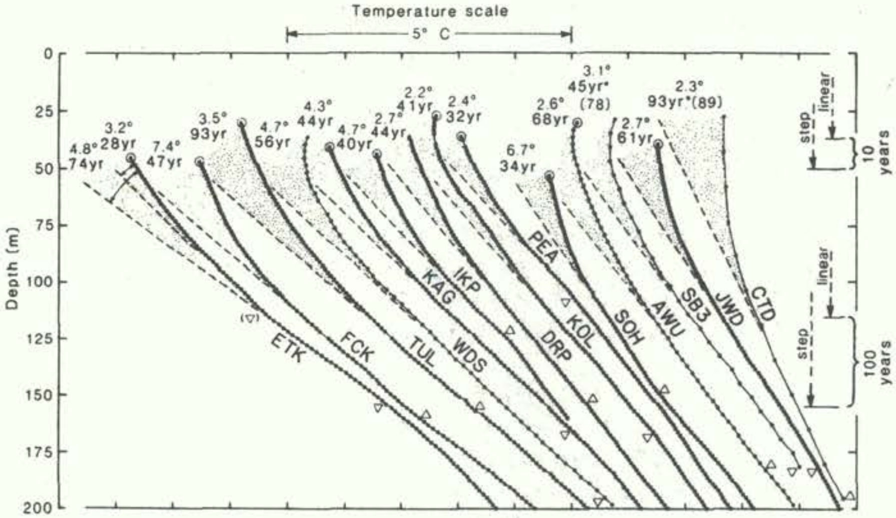


Figure 5. Data from sites denoted by ● in Fig. 1. Temperature origins are offset to avoid overlap. The stippled region for each curve is warming anomaly T(z); numbers by curves indicate total temperature increase in Celsius degrees, and time in years before August 1984 for start-up in the best fitting model of linear warming. Available shallow measurements have been deleted above circled dots for this analysis.

keep a balance sheet of fluxes at the earth's surface. Thus while the unbalanced climatic flux (C, Figure 4a) is an inconspicuous second-order effect in the climatic system, it is a conspicuous first-order effect that dominates the thermal regime of the upper 100 m in the solid-earth system (Figure 4b)--the solid earth is a good watch dog for changes in the surface energy balance. Where does this downward flowing heat go? The answer: not far in a century, the earth is a poor conductor of heat. In fact, it is all contained in the stippled region (Figure 4b), which, as far as the solid earth is concerned, is the complete climatic change from start to finish.

A broader sample of the Arctic data is given in Figure 5 which shows curves similar to the ones we have been discussing; they represent the solid dots on the map (Figure 1). On the right side of Figure 5, we show the depth to which a climatic change would be perceptible if it took place as a sudden step or as a linear change starting a decade ago (upper marks) or a century ago (lower marks). Our interpretation of the depth of the climatic anomaly is shown by the stippled regions for each of the curves. It is clear from the marginal reference alone that the durations of these changes have been large relative to a decade but not large relative to a hundred years.

Although the long-term warming to 100 m shown by these curves is widespread in the Alaskan Arctic, it is important to emphasize that it is not universal there. Counter examples occur at the points in the "shallow group" of Figure 1 (7 out of 36 sites) and other complications exist in the upper 40 m from engineering and other events of the last decade. We do not yet have enough information to map the patterns of long-term changes or, of course, to understand their causes. It is clear, however, that the presence of these systematic transient temperature anomalies in the upper 100 m of permafrost (or other impermeable formations as well) is a firm indication that the heat balance at the surface was systematically disturbed during the last century, and the absence of such signals is clear indication that it was not; this geothermal signal is a direct thermophysical consequence of the climatic thermal events we are looking for, not a "proxy" for them. It is possible at any time to obtain climatic history information for the last century "after the fact" by drilling a 200 m observation well at any location where the information is desired. An additional advantage of the geothermal method is that the earth integrates the permafrost temperature uniformly and continuously, filtering out the (high frequency) noise and preserving only the (low frequency) climatic signal, thereby sparing us a computational burden, and avoiding uncertainties that might be caused by changing measurement conditions during the accumulation of weather records over many generations.

A problem with the geothermal method is that the "surface" whose temperature is being reconstructed is not strictly the surface of the solid earth, it is the surface of permafrost (T_{pf}, Figure 6) which lies beneath an annually thawing "active layer" whose thickness varies from 0.2 m in wet areas to 2 m in dry ones. Below this surface, heat transfer is almost exclusively by heat conduction, above it is not. Most climatological studies of contemporary change are analyses of T_{air} (Figure 6) measured in a standard observatory thermometer shelter; between it and the top of permafrost are a boundary layer in the air, a seasonal snow pack and the active layer, each of which transfers heat in complex ways. Thus it might not be surprising that weather records at Barrow suggest that T_{air} did not change systematically in the last 60 years but nearby geothermal measurements suggest that T_{pf} probably did. The difference could relate to secular change in snow cover or other moisture conditions, important climatic variables in any case. To understand and monitor the presently changing arctic climate, it is important to understand the physical relations between temperatures at the top of permafrost and those routinely measured in the overlying air so that geothermally detected changes can be more directly related to the wealth of data on air temperature change.

A second obvious and important area for study is to determine how widespread the geothermal climatic effects are and what they tell us about the pattern of contemporary change. References to such change, mostly in site-specific local studies scattered throughout the geothermal literature, need to be pulled together and systematic additional measurements need to be undertaken to understand existing conditions and to monitor their future changes.

Finally, our data indicate that the permafrost surface in the Alaskan Arctic is generally warming very rapidly (∿2° to 4° C in the last century) and this implies a very rapid change in climate there. Why is this happening? Perhaps it results from a change in snow albedo due to the settling out of atmospheric pollutants, or possibly to a secular change in sea ice cover over the nearby Arctic Ocean, or to subtle changes in other parts of the climate system of the North Polar Basin. Whatever its cause may be, however, it is important that it be understood and considered in the context of predicted global change. The permafrost warming is a very measurable and conspicuous effect occurring where the global warming is expected to be greatest and first observable and in a medium, continuous permafrost, well-suited to detection and monitoring of such changes. It is important to understand the changing permafrost regime whether it is a direct effect of predicted global change or a complicating background effect upon which the predicted global change will eventually be superimposed.

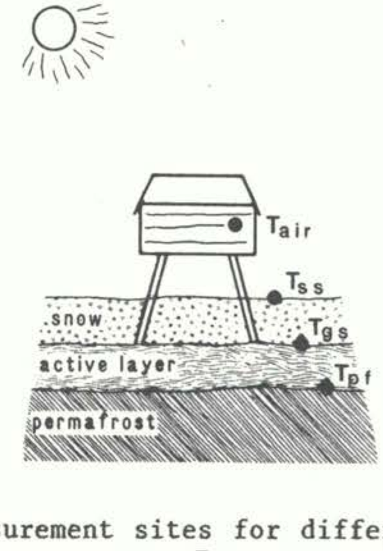


Figure 6. Measurement sites for differently defined mean annual surface temperatures: T_{pf} at upper surface of permafrost, T_{gs} at the ground surface, T_{ss} at the solid surface of the snow pack when it is present and ground surface when it is not, and T_{air} in a standard observatory thermometer shelter.

VARIATIONS IN ATMOSPHERIC CARBON DIOXIDE AND ICE AGE CLIMATE

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Climate change was for many years a neglected aspect of the earth sciences. Two developments in the last decades have raised the subject to new prominence. Scientists from a variety of fields produced evidence indicating that past epochs of glacial cold and intervening warmth were due to small deviations in the earth's orbit about the sun. Coincident with these advances in the science of ancient climate change, there grew a recognition that man, through his myriad activities, was now altering the composition of the earth's atmosphere, and that with these changes he was altering climate. Recent advances in glacial studies indicate that past climate changes are associated with changes in atmospheric composition. These findings suggest a complex cause for glacial epochs, and emphasize the importance of reducing current alterations of the atmosphere.

Variations of CO_2 with Time as Determined from Ice Cores

A glacier is renewed by the gradual solidification of fallen snow into ice. During the fall of snow and its compaction, air that is trapped will eventually form bubbles in the ice. The process, including possible seasonal melting and refreezing, may take decades or longer. When later recovered from the ice, the air contains a record of the past composition of the atmosphere. The dating of the ice proceeds by counting the annual layers.

The record of past variations of carbon dioxide and hydrogen isotopes has been significantly extended by the recent publication of three French-Soviet papers on the Vostok ice core drilled in East Antarctica.[1] The Vostok ice core has provided the deepest samples yet obtained. Its 2083 meters extend back to 160,000 before the present (BP). This time period covers the most recent glacial period, the interglacial period that preceded it, and the end of the penultimate ice sheet advance. The variations in CO_2 content with time are shown in Figure 1.

Global Carbon Cycle

Observations on trapped air from ice sheets in Greenland and Antarctica show simultaneous shifts in atmospheric CO_2 concentrations from 200 to 280 parts per million by volume (ppmv) over a period of 1000 years, or possibly less. This increase implies that 170 billion tons (Gt) of carbon were added to the atmosphere during the shift from glacial to interglacial conditions.

Within the carbon cycle (see Fig. 2), the oceans form the largest reservoir of carbon, but the highest fluxes are between the atmosphere and the land-based portion of the biosphere. The time constants for changes in land-based carbon reservoirs tend to be shorter than for oceans which have a mixing time on the order of 1000 years.[4]

Major Changes in Carbon Cycle During a Glacial to Interglacial Transition

As indicated in Figure 2, the land biomass currently stores about 560 Gt of carbon (C). Soils, including peat, hold another 1550 Gt of C. A period of glaciation could change these reservoirs in major ways. Table 1 lists the major ecosystems and the amount of carbon stored in each of them.[5]

Table 1

Distribution of Carbon in Various Ecosystems at Present

Ecosystem	Area (km^2)	Living Biomass (Gt of C)	Soil (Gt of C)
Tropical forest	24.5	189	265
Temperate forest	12	50	150
Boreal forest	12	140	230
Woodland	8.5	67	55
Tropical grassland	15	26	60
Temperate grassland	9	34	160
Tundra and Alpine	8	11	150
Desert scrub	18	5	95
Cultivated	14	30	100
Swamp and marsh	2	8	130
Extreme desert and ice	24	-	5
Totals		560	1400

During glaciation, exposure of the continental shelves by the retreating sea would provide a large area for the formation of salt marshes. Marshes have soil that is rich in carbon, typically about 72 kg m^{-2}, as opposed to the 10 kg m^{-2} for lowland tropical forest. During a period of maximum glaciation, the amount of carbon stored in soils could be expected to increase several-fold. As altered climate conditions extend tundra and boreal forest southward, the areal coverage of these ecosystems, and thus the storage pool for carbon associated with them, would also increase.

Glacial periods are characterized by widely arid conditions. One reconstruction of Africa's tropical forest coverage during glacial times shows a decrease in forest area to one-third its present size, followed by an increase 8000 years BP.[6] Vuilleumeir[7] suggests there was an even greater reduction in forest area during the arid phase in South America.

Table 2 illustrates how changes in land use during glaciation could bring about the observed decrease of approximately 170 Gt in the atmospheric carbon reservoir. During maximum glaciation, reduced tropical and temperate forest areas were made-up, in part, by greater areal coverage of tundra and boreal forest. The fourfold increase in land covered by salt marshes resulting from the lowered sea levels is considered, in this model, to have had the greatest impact on carbon storage.

Table 2

Postulated Distribution of Carbon in Various Ecosystems During Glacial Maximum

Ecosystem	Change Interglacial to Glacial	Living Biomass (Gt of C)	Soil (Gt of C)
Tropical forest	X 1/3	63	88
Temperate forest	X 1/3	25	75
Boreal forest	X 3/2	210	345
Woodlands	None	67	55
Tropical grassland	None	26	60
Temperate grassland	None	34	160
Tundra and Alpine	X 2	22	300
Desert scrub	None	5	95
Swamp and marsh	X 4	32	520
Total		484	1698

The postulated changes in land use associated with glacial advances were followed by a 16% rise in carbon in the living biomass and an 18% decrease in the mass of carbon stored in soils during glacial to interglacial shifts. In this model of on-land carbon pools, 222 Gt of carbon were subtracted from the land-based reservoirs and added to the atmosphere and oceans during interglacial epochs.

Figure 1. Variation of the carbon dioxide content of the atmosphere over the last 160,000 years as determined by measurements on air trapped in the ice core, Vostok, East Antarctica (after Barnola et al.[2]).

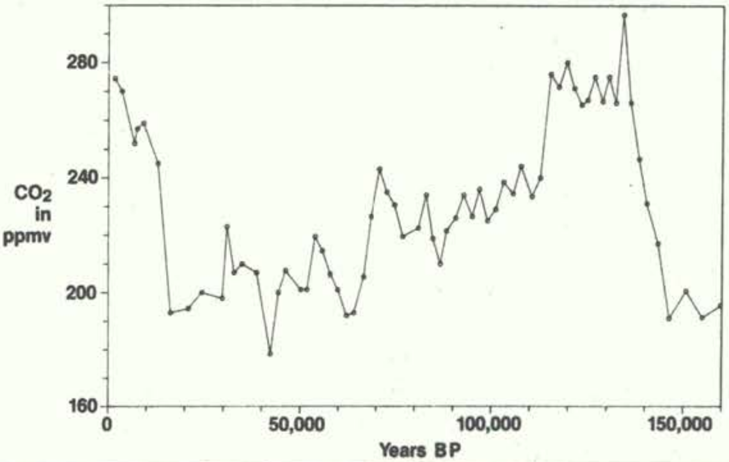


Figure 2. Land-ocean-atmosphere carbon cycle as of 1987. Units of storage are Gt; units of flux are Gt per year (revised and updated after Bolin[3]).

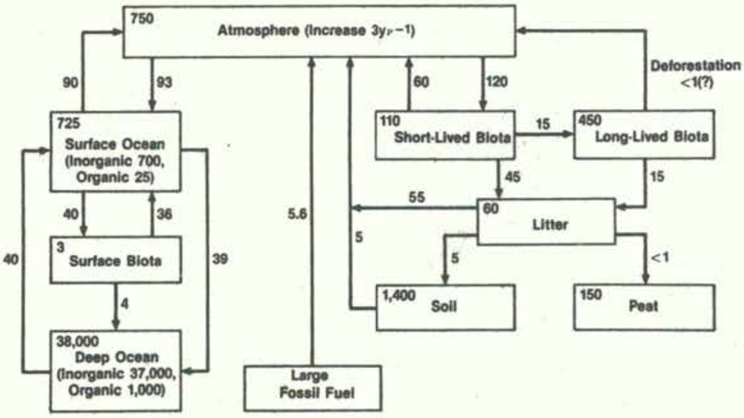
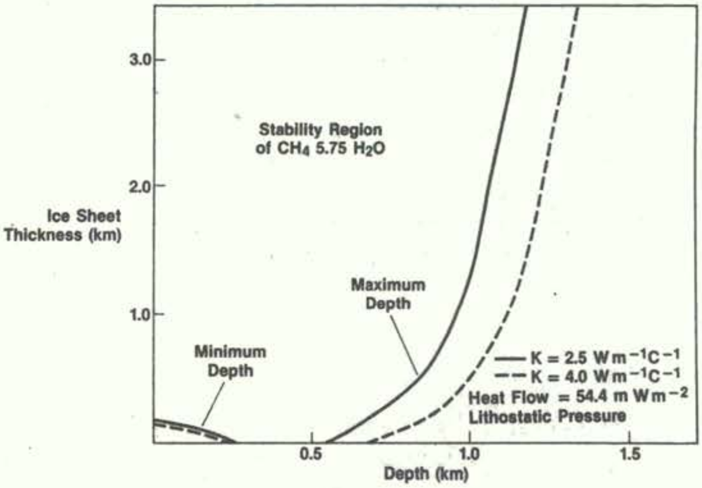


Figure 3. Stability region of methane clathrate as a function of thickness of overlying ice sheet. Temperature at the base of the ice sheet is 0° C.



Production and Storage of Methane During Glacial Periods

Glaciation would be accompanied by a significantly higher rate of methane production. Biogenic methane is generated at low temperatures during the decomposition of organic matter by anaerobic microorganisms.[8] In anaerobic environments, methane bacteria are the terminal organisms on the microbial food chain.

Wetlands are considered to be a principal source of methane. The major natural wetland regions are in coastal marshes, and boreal and low arctic ecosystems. Production rates of methane in peatlands and arctic bogs tend to be among the highest observed, up to 1.9 $gCH_4\ m^{-2}\ day^{-1}$.[9] The greater extent of such areas during glacial times, together with the vast extension of marshes onto the continental shelves, suggests that biological production of methane was significantly greater during glaciation than at present. This conjecture receives indirect support from the observation of surprisingly large amounts of natural gas of biological origin in glacial drift.[10] The gas is associated with black soils and other debris left by receding ice sheets.

The above evidence indicates that glacial epochs produced ecosystems which promoted high biological production of methane. In cold regions, anaerobic decomposition leads to high rates of methane formation. During winter, frozen marsh and wetland surfaces prevent methane from escaping to the atmosphere. At still higher latitudes, where permafrost is encountered, methane remains trapped beneath the frozen ground, even though methane production may continue at depth below the surface. Finally, water saturated with methane may form a methane clathrate,* a compound with a well-defined region of stability in the temperature-pressure plane. Water can thus crystallize as a solid at temperatures above 0°C, provided the water is methane-saturated and the pressure is high enough.

The range of stability of clathrates is dependent on subsurface thermal conductivity. Figure 3 shows two representative values of subsurface conductivities under lithostatic pressure, as well as the region of clathrate stability. In front of the glacier, if the surface temperature is 0°C, methane clathrate is stable in a layer extending from 300 to 500 m. If ground conductivity is greater than 4.0 $Wm^{-1}\ {}^\circ C^{-1}$, the layer of stability extends from 225 to 675 m in depth. If the effective pressure is only the hydrostatic pressure of the ice phase, the thickness of the stable clathrate region is less, as is illustrated in Figure 4.

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*Clathrates are commonly termed hydrates. Because hydrate refers to well-defined compounds with distinct chemical structure, the term clathrate will be used to refer to compounds in which water forms ice cages that imprison gas molecules.

The trapping and storage of carbon during a period of ice sheet advance is a complex process. Some hundreds of kilometers to the south of a glacier's terminus lies the boreal zone of bogs and marsh. Nearer to the glacier are regions of permafrost and semi-permafrost. In these regions, the combination of anaerobic conditions and cold temperatures leads to high rates of methane production. As the permafrost line advances and penetrates more deeply, the methane is trapped in water solution. As the ice sheet passes over the permafrost, the increased pressure it exerts can move the dissolved methane-water solution into the methane clathrate region of stability. Whether methane clathrates form in front of the advancing glacier or when the glacier passes overhead depends on subsurface thermal conditions. Some fraction of the methane will be stored until the ice sheet retreats. The conditions required for storage of carbon as methane during glaciation are schematically illustrated in Figure 5.

Large amounts of carbon could be stored in clathrates. A cubic kilometer of pore methane clathrate contains 91 million tons (Mt) of C. As indicated in Figure 6, it is not expected that clathrate layers would extend continuously over large areas, or that these layers would be composed purely of clathrate. However, given the large areas either covered or affected by ice sheets and the long duration (100,000 years) of the last glaciation, it is not unreasonable to suppose that at least several hundred Gt of carbon were trapped in the form of clathrate some 20,000 years ago.

Release of Methane During Retreat of the Ice Sheets

As a glacier retreats, a corresponding reduction in the area covered by permafrost will allow an increase in methane emissions. The largest increases in emissions will result from the release of methane from destabilized clathrates. The time for thermal destabilization will be on the order of d^2/α, where d is the depth and α is the thermal diffusivity. For a depth of 100 m and a thermal diffusivity of 10^{-6} m^2s^{-1}, it will take 300 years for a surface perturbation in temperature to reach the clathrates. Deeper deposits require longer times for thermal destabilization; a 600 m depth is reached after 10,000 years. Clathrates are more rapidly destabilized by a decrease in pressure. The essentially instantaneous pressure release produced by a retreating ice sheet allows clathrate decomposition to proceed rapidly near the surface, once the ice has withdrawn.

Figure 4. Methane clathrate stability region under ice sheet of varying thickness, provided the "ice phase" carries the pressure.

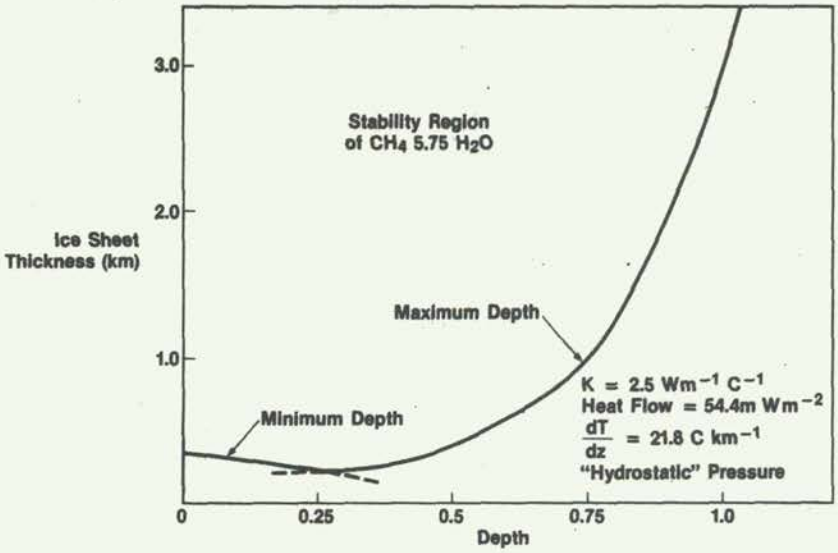


Figure 5. Schematic diagram of regions in which carbon would be stored in areas in vicinity of an ice sheet.

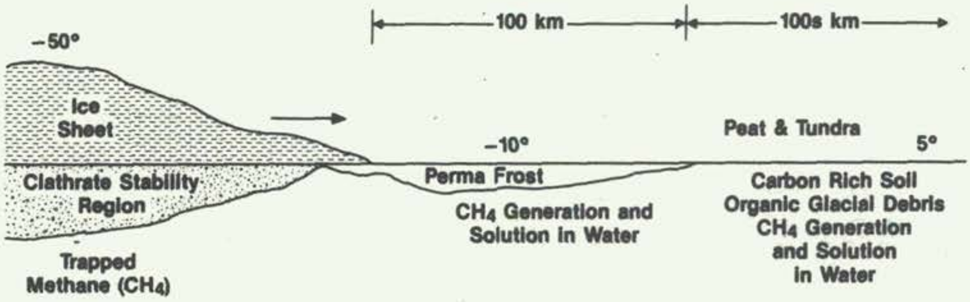
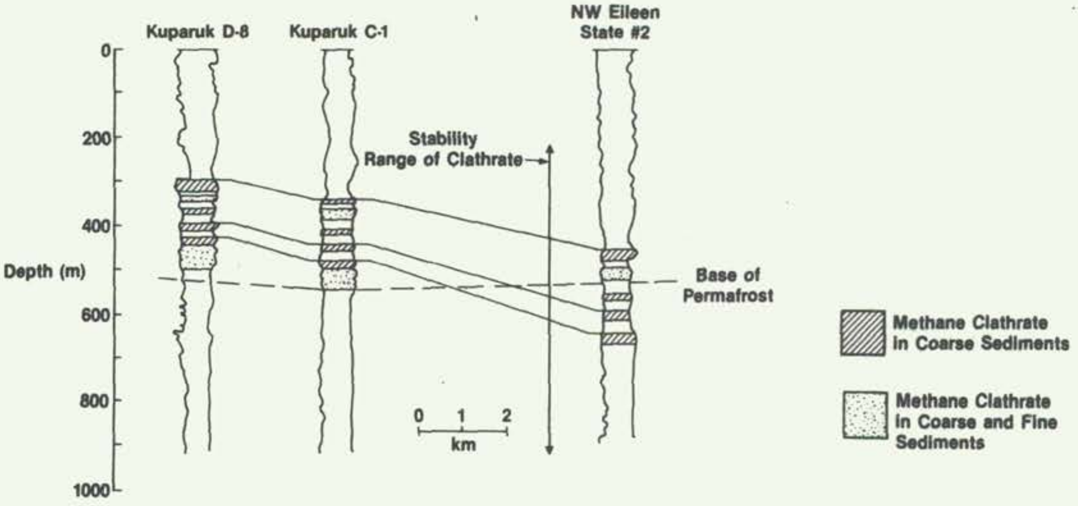


Figure 6. Land-based methane clathrate occurrences in Prudhoe Bay, Alaska (after Collett and Enliq-Economides[11]).



Summary

During glacial ages, the patterns of land-based ecosystems were vastly different than they are today. Areas of salt marsh, boreal bogs and tundra were more extensive, while tropical and temperate forests covered significantly less area than they do today. The amount of carbon stored in living biomass was some 10 to 20% less than at present, but the amount of carbon stored in swamps and peat bogs was significantly greater. The decrease in carbon stored within the atmosphere during glacial times was more than equalled by the increased carbon stored in the combined glacial reserves of biota and soil.

The changing pattern of ecosystems affected atmospheric composition. The abundance of low-temperature anaerobic environments enhanced methane production making the ground flux of methane during the last glacial period greater than during the Holocene. At present, however, the methane concentration is increasing 1 to 2% a year, so glacial atmospheric methane content may not have been as high as the present methane concentration. The greenhouse warming during glacial times due to methane was small compared to the cooling associated with the lower carbon dioxide concentration.

Atmospheric carbon was isotopically lighter during glacial times than during the Holocene due to the relatively high production of biological methane. The lighter atmospheric carbon appears to have been reflected in the oceans, as evidenced by isotopically light fossil benthic foraminefera.

A fraction of biologically produced methane was trapped in and under permafrost to form methane clathrates during glacial periods. On retreat of the ice sheets, methane was released on a short time scale of years by pressure decomposition of near-surface clathrates, and over a much longer time scale of hundreds to thousands of years by thermal decomposition of deep clathrates. Rapid, direct greenhouse warming by methane was supplemented by greenhouse warming due to methane-generated ozone. Following glacial retreat, the rise in sea level and growth of tropical forest led to lower methane concentrations, higher carbon dioxide levels and isotopically heavier carbon in the atmosphere.

The above discussion leaves unanswered the question of whether changing atmospheric composition was responsible for the retreat of the glaciers, or whether their retreat forced a change in the atmosphere. Such questions become almost irrelevant when considering large dynamical systems with many variables and strong feedbacks. Some event, either external, such as a change in solar radiation brought about by orbital fluctuation or solar activity, or internal, such as volcanic activity or nonlinearity in the ocean-atmosphere system, brought on a prolonged warm period. Once warming had increased methane

fluxes from permafrost regions, an atmospheric greenhouse warming was initiated. The strong feedback of further methane release led to rapid ice sheet retreat. The process slowed when near-surface clathrates had decomposed, leaving only the deeply buried clathrates.

Conclusions

The analysis of past climates provides insight into future climate changes that could result from man's activities. Atmospheric and ice age histories clearly establish the importance of carbon dioxide and other greenhouse gases in determining the earth's climate. Climate analysis also reveals the importance of feedbacks in the immensely complicated land-atmosphere-ocean system. Human-induced warming may accelerate thermal decomposition of clathrate buried in land areas or in sediments on continental shelves. Higher temperatures will also stimulate bacterial decomposition in soils and forest litter, which will lead to higher fluxes of carbon dioxide. These, and other--perhaps unexpected--feedbacks are sure to have significant effects on future climate.

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Sea Ice as a Potential Early Indicator of Climate Change

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Introduction

One important geophysical parameter to consider in discussions of climate change is sea ice. Sea ice extends over a vast area of the polar regions and is an integral component of the world's climate system. In the southern hemisphere, over the course of a year sea ice typically expands from a minimum areal extent of approximately 4 million square kilometers in February to a maximum areal extent of approximately 20 million square kilometers in August and September. In February the southern hemisphere ice is confined largely to the Weddell, Bellingshausen, and Amundsen seas, whereas in August and September it surrounds the Antarctic continent and extends northward to 55-65°S, with an area exceeding that of the United States and Canada combined. In the northern hemisphere, sea ice extent typically increases from approximately 8 million square kilometers in September to approximately 15 million square kilometers in March. In September the northern hemisphere ice is confined mostly to the central Arctic Ocean, whereas in March it covers almost the entire Arctic Ocean and Canadian Archipelago plus large portions of many of the peripheral seas and bays, including the Sea of Okhotsk, Bering Sea, Hudson Bay, Baffin Bay/Davis Strait, Greenland Sea, and Kara Sea.

The following sections discuss the importance of this extensive sea ice cover to the global climate system, and the likelihood that changes in the sea ice cover could prove to be early indicators of climate change.

Sea Ice As a Component of the Global Climate System

The large amount of sea ice in the northern and southern hemispheres influences the atmosphere and oceans in many ways (Barry, 1983; Parkinson et al., 1987). Several of the most important ways derive from the role of sea ice as a strong insulator, restricting exchanges of heat, mass, and momentum between ocean and atmosphere. For instance the winter turbulent heat exchanges from the surface to the atmosphere are often reduced by over an order of magnitude, from hundreds to tens of watts per meter squared, as a result of the presence of a sea ice cover. Similarly, wind-driven waves are often nearly eliminated, a fact well appreciated by individuals on ships maneuvering in sea-ice-laden waters. Additionally, the decreased evaporation from the water in the presence of a sea ice cover results in less snowfall both over the ocean and over the adjacent land surfaces.

Another important influence of sea ice derives from the fact that it reflects a much larger percentage of the incident shortwave, or solar, radiation than does open water. Reasonable estimates of the reflection percentages (or albedos) for ice-free ocean, bare ice of thickness 1 meter or more, and ice with a fresh snow cover are 5-15 %, 70-85 %, and 90-98 %, respectively, so that significantly less solar radiation is absorbed at the ocean's surface in the presence of a sea ice cover. Consequently, if an atmospheric warming were to decrease the amount of ice, this decrease would serve to intensify the warming conditions as more heat would be absorbed at the ocean's surface.

Additional impacts of the ice on the ocean sometimes extend far beyond the polar regions. The formation and aging of ice involve the rejection of salt to the underlying upper ocean and thereby increase the density of the oceanic mixed layer. This can lead to a deepening of the mixed layer and, at times, to deep oceanic convection and bottom water formation. In fact, although observations are limited, it is likely that much of the world's bottom water forms initially in polar latitudes, in the region of the sea ice cover. Thus the bottom water formed in the polar seas influences the bottom water circulation of the entire world's oceans (Killworth, 1983). Sea ice also has a tendency to reduce regional temperature contrasts by transporting cold water equatorward and to reduce seasonal temperature contrasts by releasing energy (during the change of state from liquid water to solid ice) in winter and absorbing energy (during the change of state from ice to water) in summer.

Conversely, sea ice is significantly influenced by both the atmosphere and the oceans (Barry, 1983; Parkinson et al., 1987). Ocean temperatures and salinities determine the timing of ice formation and of melt and growth at the bottom of the ice, whereas atmospheric temperatures, humidities, and cloud cover directly affect both surface ice melt and the amount of snow cover on the ice. Furthermore, winds and ocean currents are major determiners of sea ice dynamics.

For the above reasons, sea ice is seen to be an integral component of the global climate system, affecting and being affected by both the oceans and atmosphere. It is therefore reasonable to ask whether sea ice could potentially be an early indicator of climate change. This is an issue of whether climatically significant changes in the sea ice cover are likely to be detectable earlier than climatically significant changes in other components of the climate system. To be a likely candidate as an early climate-change indicator, a variable should (1) be expected to exhibit a large climate signal, (2) be routinely measurable on a global basis, so that changes will be observed, and (3) have low enough natural variability so that a climate signal will be detectable above the background noise. In the following three sections, each of these issues will be addressed in turn. It will be seen that sea ice satisfies the first two criteria very well, as numerical models indicate that sea ice should exhibit a very large climate signal and passive-microwave satellite observations allow ready monitoring of the sea ice cover, but that it is weaker regarding the third criterion.

Climate Change Simulated for the Sea Ice Regions

Although there remains considerable uncertainty, a variety of climate models and model comparisons suggest that the anticipated warming from increases in atmospheric carbon dioxide and other trace gases could be several times larger in the polar regions than in the equatorial regions (see, for instance, the modeling studies summarized by Schlesinger and Mitchell, 1985). Any temperature rise in the polar regions would affect the sea ice by reducing sea ice formation and increasing sea ice melt. The lessened amount of sea ice could then be expected to further increase polar surface air temperatures because of increasing the amount of solar radiation absorbed at the earth's surface and increasing the transfer of heat from the ocean to the atmosphere.

A numerical model of sea ice has been used to simulate what would happen to the sea ice cover if the atmospheric temperatures were to increase, as anticipated for continued increases in atmospheric carbon dioxide and other trace gases. Results will be mentioned here for the event of a 5 K temperature increase, which is half the annual average temperature increase predicted by Manabe and Wetherald (1975) for 80°N under conditions of a doubling of atmospheric carbon dioxide. The sea ice simulations suggest that in response to a 5 K surface air temperature increase, typical sea ice thicknesses in the Arctic Ocean in winter could be reduced to under a third of their current wintertime values and the Arctic ice cover, which currently spreads over 8 million square kilometers at its summer minimum, could be eliminated entirely for a portion of the summer (Parkinson and Kellogg, 1979). Results for the southern hemisphere are similarly dramatic and also include an elimination of all ice for a portion of the summer in the event of a 5 K atmospheric temperature increase. The wintertime results for the southern hemisphere show a reduction in both the total ice area and the total ice volume of about one half with a 5 K temperature increase (Parkinson and Bindschadler, 1984).

All these simulation results are subject to the many uncertainties in the models, which are discussed in the respective papers. Nonetheless, it remains clear that the likelihood exists that a global climate change, whether resulting from changes in carbon dioxide or otherwise, would be reflected in a major way in the sea ice cover of the polar regions. Thus sea ice satisfies the first of the three criteria for potential early indicators of climate change stated at the end of the previous section. In the next section it will be seen that sea ice also satisfies the second criterion, for, because of satellite technology, when large-scale changes in the sea ice cover occur, they should be easily observable.

Monitoring of the Sea Ice Cover from Satellite Observations

Sea ice is a component of the climate system which is observable from space through routine satellite observations and thereby can be monitored more easily than several of the other components of the climate system. In particular, satellite monitoring of the global sea ice cover can be obtained through passive microwave imaging, in which the satellite records radiation from the microwave region (wavelengths of 1-100 centimeters) of the electromagnetic spectrum. The ability to monitor sea ice through passive microwave technology results from the sharp contrast between the microwave emissivities of open water and sea ice, with sea ice emitting considerably more microwave radiation than does open water. For example, at a 1.55-centimeter wavelength (the wavelength of the radiation recorded by a major satellite passive microwave sensor in the 1970s), the emissivity of open water is approximately 0.4 whereas the emissivity of sea ice ranges from approximately 0.8 to approximately 0.97. This contrast between water and ice allows a ready determination of the sea ice edge from the microwave data.

In addition to the location of the ice edge, the concentration of the ice--i.e., the percentage of the ocean area covered by sea ice--is also important to climate studies. A smaller sea ice concentration implies either larger or more numerous gaps between ice floes, and this in turn allows more evaporation from the ocean surface, greater heat exchange between the ocean and the atmosphere, and greater absorption of solar radiation at the ocean's surface. Because different types of sea ice have different emission properties, determination of sea ice concentrations cannot yet be done from space as accurately as determination of the sea ice edge. However, algorithms have been and continue to be developed to calculate sea ice concentrations and other sea ice parameters from space observations through the use of data from several different microwave wavelengths (Cavalieri et al., 1984). As a result, it is possible to provide images of sea ice extent and approximate ice concentrations for both the north and south polar regions, and to do so on a routine basis, with a frequency of every few days.

Two passive microwave radiometers have provided valuable sea ice information for much of the period from 1973 through the present. The Electrically Scanning Microwave Radiometer (ESMR) launched in December 1972 on NASA's Nimbus 5 spacecraft transmitted good quality data for most of the four-year period 1973-1976, and these data, along with extensive descriptions and analyses, have been compiled into an Arctic sea ice atlas (Parkinson et al., 1987) and an Antarctic sea ice atlas (Zwally et al., 1983a). More recently, the Scanning Multichannel Microwave Radiometer (SMMR) on NASA's Nimbus 7 spacecraft has provided sea ice coverage for much of the period from its launch in October 1978 until the present. Fortunately it appears that the passive-microwave coverage of the polar regions will be continued indefinitely into the future, as a result of the recent, June 1987, launch of the Special Sensor Microwave Imager (SSMI) on a spacecraft of the U.S. Defense Meteorological Satellite Program and the inclusion of an Advanced Mechanically Scanned Radiometer (AMSR) in the plans for the Earth Observing System in the mid-1990s. Thus sea ice satisfies the second criterion--that it be routinely measurable on a global basis--mentioned above for potential early indicators of climate change.

Sea Ice Variability

Sea ice exhibits a fair amount of interannual variability, which in some ways lessens its potential as an early indicator of climate change because seemingly significant changes in the sea ice cover might not reflect climate-change scenarios. For instance the extent of Antarctic sea ice decreased noticeably in the mid-1970s, with the wintertime maximum ice extent decreasing from just over 20 million square kilometers in 1973 to 17 million square kilometers in 1977 (Kukla and Gavin, 1981; Zwally et al., 1983b). It was suggested in the early 1980s that this was perhaps the first geophysical evidence of a carbon-dioxide warming of the atmosphere; but the premature nature of this suggestion became clear when data from the late 1970s and early 1980s showed the sea ice cover rebounding back to the levels of the early 1970s (Zwally et al., 1983b). This example serves as a warning against overinterpreting apparent trends from what remains a very-short sea ice record, with global sea ice coverage from satellites being available only since December 1972.

However, analysis of the spatial changes in the sea ice cover along with the overall trends could provide a greater chance of properly interpreting possible climate-change conditions. Certain regions in both the Arctic and Antarctic exhibit important consistencies in their sea ice covers from year to year, and major changes in those aspects could reflect larger changes in the climate system. For instance, in February in the Labrador Sea and Davis Strait to the southwest of Greenland a prominent indentation of open water exists which is fairly consistently located from year to year. This indentation results from the relatively warm waters brought northward into Davis Strait by the north-flowing West Greenland Current. Should data in future years show February ice distributions to extend considerably farther south along Greenland's west coast, it could reasonably be speculated that a cutting-off, mollification, or diversion of the West Greenland Current had occurred, at least temporarily. Conversely, if the sea ice distributions showed open water extending much farther north than normal in Davis Strait and Baffin Bay, the reason could be that the West Greenland Current had strengthened. Consideration of the full hemispheric ice distributions could help determine whether such a change was locally based or part of a broader-based climate change.

Discussion

Because of the integral connection of sea ice with the rest of the climate system, interannual changes in the sea ice cover can be used as an index of more general climatic conditions in the polar regions. Thus, for example, records of the duration of sea ice in the vicinity of Iceland have been used in this sense for periods when temperature and other records were not available (Lamb, 1977). It is a separate issue, however, whether sea ice might be a likely early indicator of climate change, and it is that issue which this paper has addressed.

Three criteria have been listed for a potential early indicator of climate change: (1) the variable should exhibit a large climate signal; (2) it should be readily measurable on a global basis through routine observations; and (3) it should have low enough natural variability to allow a climate signal to be detected. Sea ice has been seen to satisfy the first two of these three criteria very well but to be weaker regarding the third criterion, as it exhibits large interannual variability. As it is likely that no variable will be found satisfying all three criteria well, concurrent consideration of several different variables, including sea ice, will probably provide the best chance for early detection of climate change. Furthermore, the limitations that sea ice exhibits regarding interannual variability can be considerably lessened by examining changes in the sea ice cover regionally as well as globally and especially by considering and intercomparing changes in regions which tend to show long-term interannual consistencies.

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CAUSES AND EFFECTS OF SEA LEVEL RISE

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Imagine a land that was not developed until the sea was already rising three or four feet every one hundred years. With shorelines retreating ten feet per year, no one would have any illusions about the permanence of coastal property: The definition of property ownership could consider the fact that the land is transitory, and houses on barrier islands could be designed so that they could be easily picked up by a crane and placed on a flat-bed truck and moved to newly created land on the bay side. Natural shorelines could be protected; with development moving back as sea level rises, there would always be room for coastal wetlands and beaches to migrate inland.

There would still probably be instances where relatively permanent structures had to be built on the shore, such as ports and hotels; but these structures would be built only if the profits were enough to pay for the likely shore-protection costs.

It is easy to imagine a situation in which a rapidly rising sea is little more than a nuisance to consider in planning coastal development. But it is also possible to imagine a situation in which it causes serious problems: The coast is built with the assumption that sea level is stable; property owners believe that their land is permanent and hence build immovable structures. As the sea level rises, they build walls to protect these structures, and the beaches and wetlands are squeezed out, or the taxpayers at large are forced to expend large sums to nourish beaches.

If the greenhouse effect leads to an accelerated rise in sea level, which of these situations is most likely to apply to the North American coast? At first glance, one might suspect the latter, because our coast was developed largely on the assumption of a stable sea level. However, we have substantial advance warning and institutions are already beginning to prepare for an acceleration of sea level rise.

This paper provides an overview of the causes and effects of the projected rise in sea level from the greenhouse effect.

CAUSES OF SEA LEVEL RISE

Past Trends

The worldwide average sea level depends primarily on (1) the shape and size of ocean basins, (2) the amount of water in the oceans, and (3) the average density of seawater; the latter two factors are influenced by climate while the first is not. Subsidence and emergence due to natural factors such as isostatic and tectonic adjustments of the land surface as well as human-induced factors such as oil and water extraction, can cause trends in "relative sea level" at particular locations to differ from trends in "global sea level."

Although changes in ocean basins have been slow, the impact of climate on sea level has been fairly rapid at times. Geologists generally recognize that during ice ages, the glaciation of substantial portions of the northern hemisphere has removed enough water from the oceans to lower sea level one hundred meters below present levels during the last (18,000 years ago) and previous ice ages. (Donn et al. 1962; Kennett 1982; Oldale 1985).

Although the glaciers that once covered much of the northern hemisphere have retreated, the world's remaining ice cover contains enough water to raise sea level over seventy-five meters (Hollin and Barry 1979). Hollin and Barry (1979) and Flint (1971) estimate that existing alpine glaciers contain enough water to raise sea level 30 or 60 centimeters, respectively. The Greenland and West Antarctic Ice Sheets each contain enough water to raise sea level about seven meters, while East Antarctica has enough ice to raise sea level over sixty meters.

There is no evidence that either the Greenland or East Antarctic Ice sheets have completely disintegrated in the last two million years. However, it is generally recognized that sea level was about seven meters higher than today during the last interglacial, which was one to two degrees warmer (Mercer 1970). Because the West Antarctic Ice Sheet is marine-based and thus vulnerable to climatic warming, attention has focused on this source for the higher sea level.

Studies combining tidal gauge measurements to estimate global sea level trends have concluded that sea level has risen 1.0 to 1.5 millimeters per year during the last century (Barnett 1984; Gornitz et al. 1982; Fairbridge and Krebs 1962). No study has demonstrated that global warming has yet caused an acceleration in the rate of sea level rise.

Impact of Future Global Warming on Sea Level

Concern about a substantial rise in sea level as a result of the projected global warming stemmed originally from Mercer (1968), who suggested that the Ross and Filchner-Ronne ice shelves might disintegrate, causing a deglaciation of the the West Antarctic Ice Sheet and a resulting six to seven meter rise in sea level, possibly over a period as short as forty years.

Subsequent investigations have concluded that such a rapid rise is unlikely. Hughes (1983) and Bentley (1983) estimated that such a disintegration would take at least two or five hundred years, respectively. Other researchers have estimated that this process would take considerably longer (Fastook 1985; Lingle 1985).

Researchers have turned their attention to the magnitude of sea level rise that might occur in the next century: thermal expansion of ocean water, melting of alpine glaciers, melting of Greenland glaciers, and minor contributions from Antarctica. Table 1 summarizes the various estimates of future global sea level rise for specific years. Using a range of estimates for future concentrations of greenhouse gases, the climate's sensitivity to such increases, oceanic heat uptake, and the behavior of glaciers, (Hoffman et al. 1983) estimated that the rise would be between 56 and 345 cm, with a rise of 144 to 217 cm most likely; however, they did not examine the impact of deliberate attempts by society to curtail emissions. Revelle (1983) estimated that the rise was likely to be 70 cm, ignoring the impact of a global warming on Antarctica; he also noted that the latter contribution was likely to be 1 to 2 m/century after 2050, but declined to add that to his estimate. The NAS Polar Board (Meier et al. 1985) projected that the contribution of glaciers would be sufficient to raise sea level 20 to 160 cm, with a rise of "several tenths of a meter" most likely. Thus, if one extrapolates the earlier NAS estimate of thermal expansion through the year 2100, the 1985 NAS report implies a rise between 50 and 200 cm. The estimates from Hoffman et al. (1986) for the year 2100 (57 to 368 cm) were similar to those by Hoffman et al. (1983) However, for the year 2025, they lowered their estimate from 26-39 cm to 10-21 cm.

Sea level in particular locations will differ from the global average rise. Many areas are sinking or rising due to factors unrelated to climate change. Moreover, removal of ice from Greenland and Antarctica will reduce the extent to which gravity pulls water toward those areas, resulting in actual drops in sea level along those coasts and nearby coasts such as Baffin Island and Cape Horn. Global warming can also change winds, currents, and rainfall patterns, which would in turn change sea level in particular areas.

Table 1. Estimates of Future Sea Level Rise (centimeters)

Year 2100 by Cause (2085 in the case of NAS 1983):

	Thermal Expansion	Alpine Glaciers	Greenland	Antarctica	Total
NAS (1983)	30	12	12	*	70
EPA (1983)	28-115	#	#	#	56-345
NAS (1985)##	-	10-30	10-30	-10-+100	50-200
Thomas (1985)	-	-	-	0-200	-
Hoffman et al. 1986	28-83	12-37	6-27	12-220	57-368

Total Rise in Specific Years:**

	2000	2025	2050	2075	2085	2100
NAS (1983)	-	-	-	-70	-	
EPA (1983)						
low	4.8	13	23	38	-	56.0
mid-range low	8.8	26	53	91	-	144.4
mid-range high	13.2	39	79	137	-	216.6
high	17.1	55	117	212	-	345.0
Hoffman et al. 1986						
low	3.5	10	20	36	44	57
high	5.5	21	55	191	258	368

NOTES:

* Revelle (1983) attributes 16 cm to other factors.

** Only EPA reports made year-by-year projections for the next century.

Hoffman et al. (1983) assumed that the glacial contribution would be one to two times the contribution of thermal expansion.

NAS (1985) estimate includes extrapolation of thermal expansion from Revelle (1983).

Sources: Hoffman et al. (1986); Meier et al. (1985);
Hoffman et al. (1983); Revelle (1983); Thomas (1985).

EFFECTS OF SEA LEVEL RISE

A rise in sea level of one or two meters would permanently inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, and increase the salinity of estuaries and aquifers.

Submergence of Coastal Wetlands

The most direct impact of a rise in sea level is the inundation of areas that had been just above the water level before the sea rose. Coastal wetlands are generally found at elevations below the highest tide of the year and above mean sea level. Thus, wetlands account for most of the land less than one meter above sea level.

Because a common means of estimating past sea level rise has been the analysis of marsh peats, the impacts of sea level rise on wetlands are fairly well-understood. For the rates of sea level rise of the last several thousand years, marshes have generally kept pace with sea level through sedimentation and peat formation (Emery and Uchupi 1972; Redfields 1972 and 1967; Davis 1985). As sea level rose, new wetlands formed inland while the seaward boundary was maintained. Because the wetland area has expanded, Titus, Henderson and Teal (1984) hypothesized that one would expect a concave marsh profile, i.e., that the area of the marsh (e.g. 0 to 1 m) is greater than the area of land found immediately above the marsh (e.g. 1 to 2 m). Thus, if sea level rose more rapidly than the marsh's ability to keep pace, there would be a net loss of wetlands. Moreover, a complete loss might occur if protection of developed areas prevented the inland formation of new wetlands. This concept is illustrated in Figure 1.

Case studies in South Carolina and New Jersey based on surveying marsh profiles (Kana et al. 1986; and 1988) support this hypothesis, as does a recent study based on topographic maps (Park et al. 1986) All of these studies suggest that a one and one-half meter rise in sea level could result in a 50-90 percent loss of coastal wetlands in the United States. The loss of wetlands would be particularly great if inland areas are developed and protected with bulkheads or levees.

Louisiana, whose marshes and swamps account for 40 percent of the coastal wetlands in the United States (excluding Alaska) would be particularly vulnerable to an accelerated rise in sea level. The wetlands there are mostly less than one meter above sea level, and are generally subsiding approximately one meter per century as its deltaic sediments compact (Boesch 1982). Until the last century, the wetlands were able to keep pace with this rate of relative sea level rise, because of the sediment conveyed to the wetlands by the Mississippi River.

Human activities, however, have largely disabled the natural processes by which coastal Louisiana might keep pace with sea level rise. Dams, navigation channels, canals, and flood protection levees have interrupted the flow of sediment, freshwater, and nutrients to the wetlands. As a result, over 100 square kilometers of wetlands convert

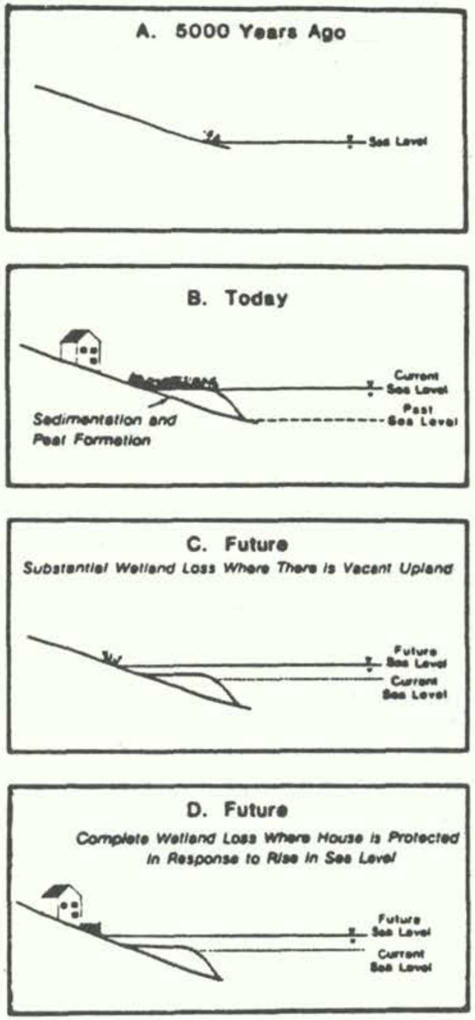

Figure 1. Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands were inundated, resulting in much more wetland acreage than dry land just above wetlands (A and B). If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract (C). Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas (D).

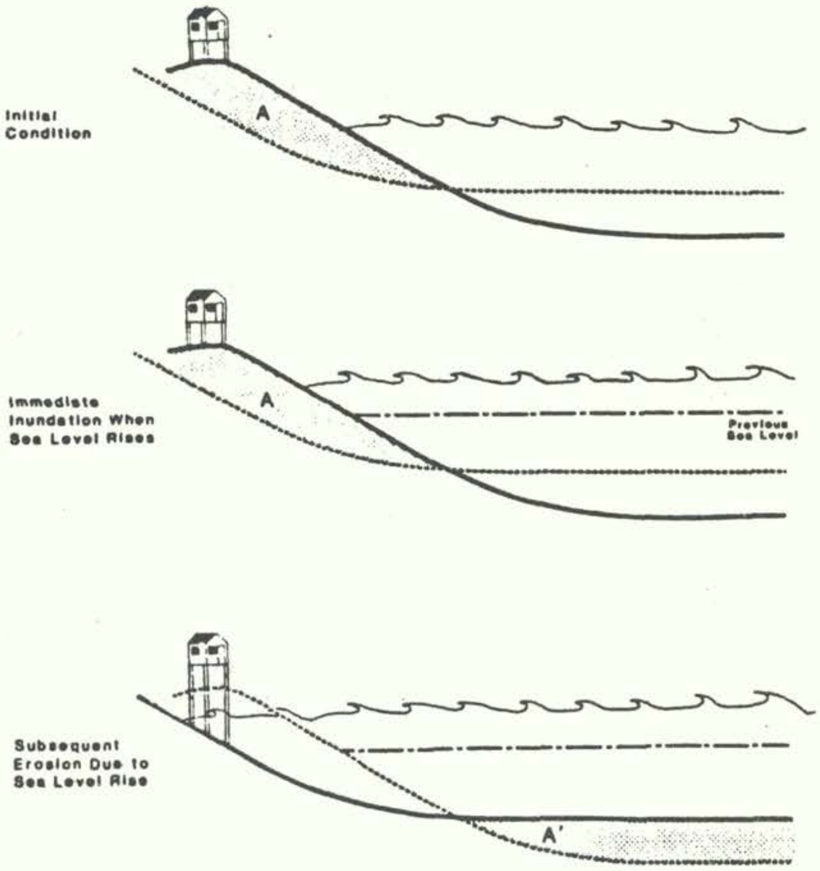

Figure 2. The Bruun Rule

to open water every year (Gagliano et al. 1981). A substantial rise in sea level would further accelerate the process of wetland loss in Louisiana. Other deltas throughout the world would be similarly vulnerable.

Several options have been identified for reducing wetland loss due to sea level rise. Abandonment of developed areas inland of today's wetlands could permit new wetlands to form inland. In some cases, it might be possible to enhance the ability of wetlands to accrete vertically by spraying sediment on them or--in the case of Louisiana and other deltas--restoring the natural processes that would provide sediment to the wetlands. Finally, some local government in Louisiana have proposed the option of artificially controlling water levels through the use of levees and pumping stations (Edmonson and Jones 1985).

The need for anticipating sea level rise would vary. Artificial means to accelerate wetland accretion need not be implemented until the rise takes place (although a lead time would be necessary to develop the required technologies). Similarly, levees and pumping stations could be delayed. On the other hand, a planned retreat would require several decades lead time, so that new structures were designed to be moved and immovable structures had time to be depreciated.

In my view, the most practical measure that could be taken today would be to generally implement an idea I proposed several years ago (Titus 1984, 1986): With the exception of heavily urbanized areas, if sea level rises enough to flood a property, the structures on that property would have to be removed and the land would revert to the state. This is better than creating buffer zones today for several reasons. First, prohibiting development on someone's property is likely to be an unconstitutional taking if applied to land that is not threatened today, which means that governments would have to buy coastal property, which would be extremely expensive. Second, the proper size of a buffer zone would be difficult to calculate since it would depend on how much the sea is going to rise and how far into the future one is willing to worry about. Finally, if we are wrong and it turns out that the sea rise does not accelerate, buying large buffer zones would be a waste of money.

By contrast, the conditional land use proposal will only impose costs on a property owner if the sea actually rises enough to inundate that property. Because it would not take effect for 50-100 years, the present value of such a policy would be a fraction of 1 percent of a property's value, and hence too trivial for courts to consider it a taking. Finally, this approach allows the market to adjust according to its own perception of the likelihood of sea level rise and the present value of future events. This practice has been recently implemented to a large degree by the state of Maine (See Morgenstern, this volume; Maine 1987).

Coastal Erosion

Sea level rise can also result in the loss of land above sea level through erosion. Bruun (1962) showed that the erosion resulting from a rise in sea level would depend upon the average slope of the entire beach profile, shown in Figure 2. By comparison, inundation depends only on the slope immediately above the original sea level. Because beach profiles are generally flatter than the the portion of the beach just above sea level, the "Bruun Rule" generally implies that the erosion from a rise in sea level is several times greater than the amount of land directly inundated.

The Bruun Rule has been applied to project erosion due to sea level rise for several areas. Bruun (1962) found that a 1 cm rise in sea level would generally result in a 1 meter shoreline retreat, but that the retreat could be as great as 10 meters along some parts of the Florida coast. Everts (1985) and Kyper & Sorensen (1985) however, found that along the coasts of Ocean City, Maryland and Sandy Hook, New Jersey, respectively, the shoreline retreat implied by the Bruun Rule would be only about 75 cm. Kana et al. (1984) found that along the coast of South Carolina, the retreat could be 2 meters. The U.S. Army Corps of Engineers (1979) indicated that along the coast of San Francicso, where larger waves are generally found than along the Atlantic Coast, the shore might retreat 2 to 4 meters for a 1 cm rise in sea level.

Relatively few of the most intensely developed resorts along the U.S. coast have beaches wider than about 30 meters at high tide. Thus, the rise in relative sea level of 30 cm projected in the next forty to fifty years could erode most recreational beaches in developed areas, unless additional erosion response measures are taken.

Responses to coastal erosion have long been a major responsibility of the U.S. Army Corps of Engineers, and have thus been thoroughly studied (U.S. Corps of Engineers 1977). The responses fall generally into three categories: walls and other structures, adding sand to the beach, and abandonment. Although seawalls have been used in the past, they are becoming increasingly unpopular among shore communities because erosion can proceed up to the wall, resulting in a complete loss of beach, which has happened, for example, at Sea Bright, New Jersey (Kyper and Sorensen 1985; Howard et al. 1985). A number of other structures have been used to decrease the ability of waves to cause erosion, including groins (jetties) and breakwaters. Bulkheads are often used where waves are small. (Sorensen et al. 1984).

A more popular form of erosion control has been the placement of sand onto the beach. Although costs can exceed one million dollars per mile, (Corps of Engineers 1980; Howard et al. 1985) it is often justified by the economic and recreational value of beaches. A recent study of Ocean City, Maryland, for example, concluded that the cost of holding back the sea for a 30 cm rise in sea level would be about 25 cents per visitor, less than 1 percent of the cost of a trip to the beach (Titus 1985). That community also provides an example of the practical consequences of sea level rise. Until 1985, the state of Maryland's policy for erosion control was the construction of groins, which curtail erosion caused by sand moving along the shore, but not erosion caused by sea level rise. Consideration of sea level rise was cited as motivating the state to abandon the groin plan and use beach replenishment, which can effectively control erosion caused by both types of erosion (Associated Press 1985).

Although shore protection is often cost-effective today, the favorable economics might change in the future. A more rapid rise in sea level would increase the costs of shore protection. A number of states have adopted erosion policies that assume a retreat from the shore. North Carolina requires homes that can be moved to be set back from the shore equal to thirty years of erosion, while high-rises must be set back sixty years. Maine requires people to demonstrate that new structures will not erode for one hundred years (Maine 1987). Other jurisdictions discourage the construction of bulkheads and seawalls (Howard et al. 1985).

The need for anticipating erosion caused by sea level rise varies. Where communities are likely to adapt to erosion, anticipation can be important. The cost and feasibility of moving a house back depends on design decisions made when the house is built. The willingness of people to abandon properties depends in part on whether they bought land on the assumption that it would eventually erode away or had assumed that the government would protect it indefinitely. Less anticipation is necessary if the shore will be protected; sand can be added to the beach as necessary. Nevertheless, some advanced planning may be necessary for communities to know whether retreat or defending the shore would be least economic.

FLOODING AND STORM DAMAGE

A rise in sea level could increase flooding and storm damages in coastal areas for three reasons: erosion caused by sea level rise would increase the vulnerability of communities; higher water levels would provide storm surges with a higher base to build upon; and higher water levels would decrease natural and artificial drainage.

The impact of erosion on vulnerability to storms is generally a major consideration in proposed projects to control erosion, most of which have historically been funded through the U.S. Army Corps of Engineers. The impact of sea level rise, however, has not generally been considered separately from other causes of erosion.

The impact of higher base water levels on flooding has been investigated for the areas around Charleston, South Carolina and Galveston, Texas (Barth and Titus 1984). Kana et al. (1984) found that around Charleston, the area within the 10-year flood plain would increase from 33 percent in 1980, to 48, 62, and 74 percent for rises in sea level of 88, 160, and 230 cm, respectively, and that the area within the 100-year flood plain would increase from 63 percent to 76, 84, and 90 percent for the three scenarios. Gibbs (1984) estimated that even an 88 cm rise would double the average annual flood damages in the Charleston area (but that flood losses would not increase substantially for higher rises in sea level because shoreline retreat would result in a large part of the community being completely abandoned.) Leatherman (1984) conducted a similar analysis of Galveston Island, Texas. He estimated that the area within the 100-year flood plain would increase from 58 percent to 94 percent for an 88 cm rise in sea level, and that for a rise greater than one meter, the Galveston seawall would be overtopped during a 100-year storm.

In addition to community-wide engineering approaches, measures can also be taken by individual property owners to prevent increased flooding. In 1968, the U.S. Congress created the National Flood Insurance Program to encourage communities to avoid risky construction in flood-prone areas. In return for requiring new construction to be elevated above expected flood levels, the federal government provides flood insurance, which is not available from the private sector. If sea level rises, flood risks will increase. In response, local ordinances will automatically require new construction to be further elevated and insurance rates on existing properties will rise unless those properties are further elevated. As currently organized, the National Flood Insurance Program would react to sea level rise as it occurs. Various measures to enable the program to anticipate sea level rise have been proposed, including warning policy holders that rates may increase in the future if sea level rises; denying coverage to new construction in areas that are expected to be lost to erosion within the next thirty years; and setting premiums according to the average risk expected over the lifetime of the mortgage (Howard et al. 1985; Titus 1984).

Studies of Charleston and Fort Walton Beach, Florida have examined the implications of sea level rise for rainwater flooding and the design of coastal drainage systems. Waddell and Blaylock (n.d.) estimated that a 25-year rainstorm would result in no damages for the Gap Creek watershed in Fort Walton Beach. However, a rise in sea level of 30 to 45 cm would result in damages of 1.1-1.3 million dollars in this community of 4,000 residents during a 25-year storm. An upgrade costing $550,000, however, would prevent such damages.

LaRoche and Webb (1985), who had previously developed the master drainage plan for Charleston, South Carolina, evaluated the implications of sea level rise for the Grove Street watershed in that community (See also Titus et al. 1987). They estimated that the costs of upgrading the system for current conditions would be $4.8 million, while the cost of upgrading the system for a 30-cm rise would be $5.1 million. If the system is designed for current conditions and sea level rises, the system would be deficient and the city would face retrofit costs of $2.4 million. Thus, for the additional $300,000 necessary to upgrade for a 30 cm rise, the city could ensure that it would not have to spend an additional $2.4 million later. Noting that the decision whether to design now for a rise in sea level depends on the probability that sea level would rise, they concluded that a 3 percent real social discount rate would imply that designing for sea level rise is worthwhile if the probability of a 30 cm rise by 2025 is greater than 30 percent. At a discount rate of 10 percent, they concluded, designing for future conditions is not worthwhile.

Increased Salinity in Estuaries and Aquifers

Although most researchers and the general public have focused on the increased flooding and shoreline retreat associated with a rise in sea level, the inland penetration of saltwater could be important in some areas.

A rise in sea level increases the salinity of an estuary by altering the balance between freshwater and saltwater forces. The salinity of an estuary represents the outcome of (1) the tendency for the ocean salt water to completely mix with the estuarine water and (2) the tendency of freshwater flowing into the estuary to dilute the saline water and push it back toward the ocean. During droughts, the salt water penetrates upstream, while during the rainy season, low salinity levels prevail. A rise in sea level has an impact similar to decreasing the freshwater inflow. By widening and deepening the estuary, sea level rise increases the ability of saltwater to penetrate upstream.

The implications of sea level rise for increased salinity have only been examined in detail for Louisiana and the Delaware Estuary. In Louisiana, saltwater intrusion is currently resulting in the conversion of cypress swamps--which can not tolerate saltwater--to open water lakes, as well as the conversion of fresh and intermediate marsh to marsh with greater salinity levels. Although the cause of the saltwater intrusion has been primarily the dredging of canals and the sealing off of river distributaries that once provided the wetlands with fresh water, relative sea level rise is gradually increasing the saltwater force in Louisiana's wetlands; a further rise in sea level would accelerate this process.

The impact of current sea level trends on salinity has been considered in the long-range plan of the Delaware River Basin Commission since 1981 (DRBC 1981). The drought of the 1960s resulted in salinity levels that almost contaminated the water supply of Philadelphia and surrounding areas. Hull and Tortoriello (1979) found that the 13 cm rise projected between 1965 and 2000 would result in the "salt front" migrating two to four kilometers farther upstream during a similar drought. They found that a moderately sized reservoir (57 million cubic meters) to augment river flows would be needed to offset the resulting salinity increases. Hull et al. (1986) estimated that 73-cm and 250-cm rises in sea level would result in the salt front migrating an additional fifteen and forty kilometers, respectively, during a repeat of the 1960s drought. They also found that the health-based 50 ppm sodium standard (equivalent to 73 ppm chloride) adopted by New Jersey would be exceeded 15 and 50 percent of the time.

Hull and Titus (1986) examined the options by which various agencies might respond to increased salinity in the Delaware estuary. They concluded that planned but unscheduled reservoirs would be more than enough to offset the salinity increased from a one-foot rise in sea level, although those reservoirs had originally been intended to meet increased consumption. They noted that construction of the reservoirs would not be necessary until the rise became more imminent. However, they also concluded that additional reservoir sites should be identified, to ensure that future generations retained the option of building additional reservoirs if necessary.

Other Impacts of the Greenhouse Warming

The impacts of sea level rise on coastal areas, as well as their importance, is likely to depend in part on other impacts of the greenhouse warming. Although future sea level is uncertain, there is a general consensus that a global warming would cause sea level to rise; by contrast, the direction of most other changes is unknown.

One of the more certain impacts is that most areas will be warmer. For coastal resorts north of Florida, the beach season would be extended by a number of weeks. For densely-developed communities like Ocean City with a three-month peak season, such an extension might increase revenues 10 to 25 percent, far more than the estimated cost of controlling erosion. Some areas where the ocean is too cold to swim today might find water temperatures more appealing in the future. Warmer temperatures in general might encourage more people to visit beaches in the summer.

Changing climate could alter the frequency and tracks of storms. Because hurricane formation requires water temperatures of 27 degrees C or higher (Wendland 1977), a global warming might result in an extension of the hurricane season and in hurricanes forming at higher latitudes. Besides increasing the amount of storm damage, increased frequency of severe storms would tend to flatten the typical beach profile, causing substantial shoreline retreat unless additional sand was placed on the beach. A decreased frequency of severe winter storms might have the opposite impact at higher latitudes.

Because warmer temperatures would intensify the hydrologic cycle, a global warming might result in increased rainfall in maritime environments. Thus, rainwater flooding could be increased both due to decreased drainage and increased precipitation. The impact of sea level rise on saltwater intrusion could be offset by decreased drought frequency or exacerbated by increased drought frequency.

WHEN TO RESPOND

The potential consequences of accelerated sea level rise are at best uncertain, in some cases speculative, and in all cases at least a few decades in the future. However, it does not logically follow that actions to address these risks must wait until the problems are more conclusively established and closer at hand. Many of the potential responses are so inexpensive today compared with the cost of implementing them later that it is more rational to prepare now than to await further information. This is especially true with respect to land-use policies to protect coastal wetlands, where the cost will be zero if the sea does not rise, and in the design of major structures with long lifetimes, where retrofitting the system to accommodate sea level rise will be several times as expensive as taking it into consideration in the initial design.

The forces of inertia make it difficult to plan for a new potential risk; but events suggest that sea level rise is one of those risks where planning is possible. People can visualize it, joke about it, and become interested in it. True: this situation always leads to a bit of sensationalism; none of us like to be tagged with the label "alarmist". Yet the ability of this issue to capture people's imagination is likely to be just as important as the results of scientific investigations in the overall effort to implement a rational response.

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EFFECTS OF SEA LEVEL RISE ON BEACHES AND COASTAL WETLANDS

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Introduction

During the past century, worldwide sea level has risen about one-half foot. Along the U.S. mid-Atlantic coast, records show that the regional trend has been a doubling of this rate. In coastal Louisiana, it has been larger by a factor of 10 due to local subsidence. These substantial differences in the rate of relative sea level rise must be considered in relationship to human usage of the land in developing proper responses.

The general effect of sea level rise on coastal lowlands is to induce landward retreat -- beaches erode and marshes are lost. Most sandy shorelines worldwide have experienced recession during the past century. Such has also been the case along the U.S. coasts; historical data indicate that about 90 percent of our sandy beaches are eroding. Accelerated sea level rise due to greenhouse-induced global warming will only increase erosion rates and exacerbate the present shoreline dilemma. Also, coastal marshlands will be lost at ever-increasing rates, with the nation's marshes perhaps disappearing at the high rates of loss presently experienced in Louisiana.

Coastal Wetlands

Coastal wetlands account for much of the land less than 5 feet above sea level. These extensive marshes, swamps, and mangrove forests fringe most of the U.S. coastline, particularly along the Atlantic and Gulf coasts. These areas are vital to our fisheries industry, maintenance of water quality, and are important in coastal recreation.

There have been significant losses of wetlands due to filling marshlands for urbanization as well as through the construction of canals and waterways and, in some cases, diversion of river-borne sediments offshore (e.g., the Mississippi River). Most of these early practices have been discontinued on a nationwide basis in response to various federal and state programs. However, land losses in Louisiana are continuing at extremely high rates, amounting to thousands of acres per year.

Salt marshes exist in a delicate balance with water levels. With gradual sea level rise (due to local subsidence or worldwide changes), marshes can generally keep pace by trapping sediments in the water column and through accumulation of their own organic material (dead stems and leaves). However, an imbalance can develop if sea levels rise significantly faster than deposition on the marsh surface, eventually resulting in waterlogging and loss.

With respect to sea level rise, coastal marshes can be broadly divided into backbarrier marshes, estuarine (brackish) marshes, and tidal freshwater marshes.

Backbarrier marshes occur along the bay sides of barrier systems of the Atlantic and Gulf coasts. Maintenance of these marshes in these dynamic environments is more a function of barrier stability than the pace of upward growth of the marsh surface, since sediment supplies are ample. For barriers that are rapidly migrating landward, there may be a net decline in backbarrier marshes as found at northern Assateague Island, Maryland. Elsewhere, marshes are exposed to the high energy surf as the barrier core has been completely eroded away (e.g., sections of the Virginia barrier islands, parts of the South Carolina and Georgia coasts). Coastal barriers along the Louisiana coast are eroding at extremely high rates, amounting to 30+ feet per year. Loss of these protective landforms will result in increased loss of marshlands.

Brackish marshes are an integral component of major estuarine systems, such as the Chesapeake and San Francisco Bays. At present, most of these estuarine marshes receive adequate sediment to compensate for current sea level rise. This must have been the case during the last century since "natural" marsh loss has not historically been reported to be a problem. Notable exceptions include the Blackwater marsh (a major Atlantic coast flyway for waterfowl in the U.S. Fish and Wildlife Refuge system) and coastal Louisiana. In Louisiana, widespread wetlands loss is in part attributable to a sediment deficiency (the summation of a number of complex, human-induced factors).

Tidal freshwater marshes are located in the upper reaches of estuaries and other low areas where salinities are less than five parts per thousand. The effect of rising sea levels will be saltwater intrusion and displacement by higher salt-tolerant plants. Canalization for oil drilling activities in the Mississippi delta has had a dramatic effect on the local ecology in this regard.

Land losses in most wetlands result from a combination of mechanisms, with shoreline erosion at the seaward edge of the marsh being the most obvious process. This factor can be expected to accelerate with increased water levels, but shoreline erosion probably accounts for only a few percent of all marsh losses annually. Most marshes will be long since submerged before extensive shoreline erosion occurs.

A more probable catastrophic mechanism of marsh loss with a significant increase in sea levels (e.g., several feet) will be formation of extensive interior marsh ponds. These shallow-water bodies enlarge and coalesce at the expense of marsh vegetation in response to rapid coastal submergence. The magnitude of such losses can be quite extensive as shown by studies at the Blackwater Wildlife Refuge in Maryland, where over one-third of the total marsh area (about 5,000 acres) was lost between 1938 and 1979 by this process (Stevenson et al, 1986). These marshes are being lost because sea levels outpace the ability of the marsh to maintain elevation, ultimately resulting in root death of the marsh plants.

Beaches and Coastal Barriers

Sea level rise will have a different effect along various portions of the U.S. coastline, depending on such conditions as sediment supply and coastal configuration. It is possible to divide the coasts into physiographic regions for consideration of their response to relative sea level rise. For instance, conditions in Louisiana do not apply to the coast of Maine because the Mississippi delta region is very flat, undergoing pronounced compaction and subsidence, while northern New England is characterized by non-erodible cliffs and portions are experiencing regional (neotectonic) uplift. This general assessment of the U.S. coast's response to accelerated sea level rise is presented elsewhere (National Research Council, 1987).

The present rise in water level is a complex phenomenon, including local, regional, and global components. Shoreline position will respond to the cumulative effect of vertical motions, termed the relative sea level rise, regardless of the cause. Rising relative sea level tends to cause shoreline recession, except where this trend is offset by an influx of sediment (naturally by river-borne sand deposition or artificially by beach nourishment).

Rising sea level is accompanied by a general recession of the shoreline due to inundation or erosion. Inundation is the submergence of the otherwise unaltered shore, while erosion is the physical removal of beach material. Direct submergence of the land occurs continuously through time and is particularly evident in coastal bays. Submergence, however, accounts for only a small portion of the net shore recession along open ocean, sandy beaches and barriers.

The primary reason that a sea level rise would induce beach erosion is that natural beach profiles are concave upward; this geometry results in wave energy being dissipated in a smaller water volume than without sea level rise, and thus the turbulence generated within the surf zone is greater. The profile responds by conforming to a more gentle nearshore slope, which requires additional sediment to be eroded from the beach.

Most sandy shorelines worldwide have retreated during the past century. Progradation has been restricted to coastal areas where excess sediment is supplied by river sources or where the land is being elevated due to uplift in some northern regions (e.g., Maine). Human interference cannot be considered a primary cause of erosion since retreat also occurs on sparsely populated and little-developed sandy coasts. Such recession could result from an increase in storminess, but this trend would have to be almost worldwide to account for erosion on geographically dispersed sandy shorelines. Therefore, in view of the demonstrated general relative rise of sea level along the U.S. shoreline, the link between shore retreat and sea level rise is based on more than circumstantial evidence; it can be stated that the relationship is causal in nature.

In some areas, it is clear that human actions have caused substantial erosional pressures. Undoubtedly the principal problem has been construction of jettied inlets and deepening of channel entrances for navigation. Along shorelines with high rates of longshore sediment transport, these constructed features trap sediment at the updrift jetty and, if material dredged from the navigation channel is not placed on the downdrift beaches, cause an amount of downdrift erosion equal to the reduction in transport. At some Florida entrances, tens of millions of cubic yards of dredged material have been dumped offshore and thus are permanently removed from the beach. This has resulted in very high erosion concentrated downdrift of tidal inlet entrances.

Historical data (maps and aerial photographs) can be used to determine rates of shoreline change (Leatherman, 1983). Over one hundred years of record are available for the U.S. coasts from the National Ocean Service of the National Oceanic and Atmospheric Administration (NOAA). This accurate informational base has been utilized for large stretches of the coastline (including much of the U.S. Atlantic and parts of the Gulf and Pacific coasts) to determine historical rates of beach erosion and barrier recession.

The national (unweighted) average rate of shoreline recession is slightly more than one foot per year (May et al, 1983). Along the Atlantic coast, beach erosion has historically amounted to about two to three feet per year, with the Virginia barrier islands exhibiting the highest rates of erosion (tens of feet per year). The Gulf coast states are distinguished by having the highest average erosion rate in the nation (over five feet per year). While parts of the Florida panhandle are fairly stable or only slightly eroding, the deltaic coast of Louisiana is by far the most dynamic (15 feet/year of erosion on average). The Pacific coast is essentially stable on average, considering the fact that more than half of the shore is hard rock. Locally, there are severe erosion problems (e.g., Oceanside, CA), and winter storms have caused dramatic losses of very valuable property in recent years where the beaches are already quite narrow (e.g., Malibu during the 1981-82 storm season).

A number of techniques have been developed to project shoreline retreat due to sea level rise (National Research Council, 1987). Accelerated sea level rise due to the greenhouse effect will increase the erosion rate and cause stable beaches to begin eroding. Based upon the projected rates of sea level rise, it is estimated that sandy beaches will erode at two to five times their current rate. This portends major problems for low-lying areas, such as coastal Louisiana, and increased problems at such beach resorts as Ocean City, Maryland, where the historical rate of beach erosion has amounted to two feet per year (Leatherman, 1986). Many of the urbanized beaches along the East and Gulf coast barrier chain are already critically narrow and in need of beach nourishment to protect the existing buildings and infrastructure. Such is the case at Ocean City, Maryland, where a $30 million beach fill project is scheduled to begin next spring. Elsewhere, many other recreational beaches have been nourished (e.g., Atlantic City, NJ; Myrtle Beach, SC; Miami Beach, FL). The expected lifetime of nourished beaches will be greatly foreshortened by accelerated sea level rise, increasing the frequency and magnitude and hence the cost of such activities.

Responses

A significant portion of the nation's population lives within the coastal zone, with many buildings and facilities built at elevations less than 10 feet above mean high tide level along the shoreline. Presently, many of these structures are not adequately above existing water levels or located far enough landward to adequately ensure their survival and safety of the people during major storm activity. This hazard has grown increasingly apparent and serious along much of the U.S. East and Gulf coasts, particularly the highly urbanized sandy barriers, as relative sea levels have risen during the twentieth century.

Residential houses and other buildings have been drawn close to the water's edge as the beaches have eroded. In an attempt to insure that future coastal structures are built stronger and above the present 100-year flood levels, the Federal Emergency Management Agency (FEMA) has been charged with providing federal flood insurance to these properties. This flood insurance program was developed to address the problem of river floods, and later expanded to include open coast, beachfront communities. Today, properties worth billions of dollars are Federally insured, making this the second largest national liability after Social Security. Unfortunately, FEMA has only adopted the flood levels approach in establishing insurance rates, which works well in river floodplains, but does not consider the fact and importance of beach erosion. Eventually a stable building and a retreating shoreline will merge, and there are numerous places along the U.S. coast where houses are standing on the beach or in the water (e.g., Westhampton Beach, NY; South Bethany Beach, DE; Folly Island, SC; Sargents Beach, TX). FEMA needs to utilize the existing erosion data and future projections of beach recession to adjust their policies and insurance rates through the development of an E (Erosion) Zone.

There are three general responses to accelerated shoreline erosion: (1) retreat from the shore, (2) armor the coast, or (3) nourish the beach. The choice of a response strategy will depend upon a number of factors, including socioeconomic and environmental conditions. The decisions reached will likely be site-specific so that each area/community must be evaluated separately.

For highly urbanized areas, such as Miami Beach, FL or Ocean City, MD, the abandonment option is not realistic. The value of such beachfront property with high density and high-rise structures often approaches $100 million per mile, making beach restoration the most attractive alternative. Elsewhere, sea walls have been constructed to stabilize the shore and protect coastal communities from the ravages of major hurricanes (e.g., Galveston, TX). For eroding shorelines that are less developed, the decision becomes more difficult. Therefore, the costs and benefits of protection must be weighed against those of retreating from the shoreline.

Conclusions

1. Worldwide sea levels have risen about one-half foot in the past century. The rates have been variable along the U.S. coasts for a number of reasons, but have amounted to one foot per hundred years along the mid-Atlantic coast. The rate of relative sea level rise in coastal Louisiana is about 10 times greater than the worldwide average due to subsidence.

2. The general response of low-lying lands to sea-level rise is retreat via beach erosion and wetlands loss. Already extensive coastal marshes are being lost in Louisiana, and it is expected that many of the barrier systems on this deltaic coast will break-up and disappear in the next half century. Extensive salt marsh loss has also been reported in the Maryland

Chesapeake Bay (over 5,000 acres lost at Blackwater marsh, mostly occurring during the past 40 years).

3. The prospect for coastal wetlands is bleak in light of existing conditions and projected changes (e.g., greenhouse effect). Marshes in Louisiana, for example, are not able to keep pace with relative sea level rise, and are presently being drowned in place. A rapidly subsiding land surface or accelerated sea level rise can yield similar results. There will be substantial losses of coastal marshes in the future.

4. Approximately 90 percent of the nation's sandy beaches are experiencing erosion. Historical shoreline studies indicate a wide range in erosion rates (essentially stable to over 30 feet per year). The Atlantic coast average is between two and three feet of beach erosion per year, the Gulf coast exceeds five feet per year, and the Pacific coast is stable on average (much of the shore is hard rock).

5. Accelerated sea level rise due to the greenhouse effect will at least double and perhaps quadruple erosion rates, depending upon which rise rate is actually realized.

6. There are three general categories of human response to shoreline recession: (1) retreat from the shore, (2) armor the coast, (3) nourish the beach. The proper response will be site-specific on a community or coastal sector basis due to large differences in environmental and socioeconomic factors. The abandonment alternative is not realistic for highly urbanized beaches, like Miami Beach, FL and Atlantic City, NJ. For less developed areas along eroding shorelines, the decision becomes more difficult. Therefore, the costs and benefits of stabilization vs. retreat must be carefully considered as the cost in either case is likely to be quite high.

7. The apparent national desire to live in the coastal zone has long term and expensive consequences. The Federally-insured flood program is already burdened with billions of dollars of insured properties close to the water's edge. Accelerated sea level rise due to the greenhouse effect will further jeopardize these vulnerable properties, eventually resulting in massive destruction (without ameliorating action) during future major storms at great expense to the American taxpayer.

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LOW COUNTRIES AND HIGH SEAS

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1. The problem

A higher sea level due to global warming will create serious problems in numerous low-lying areas around the world, especially in deltaic areas which are generally densely populated and extremely (food) productive. The problems will be worst in developing countries where lack of land and overpopulation are the driving forces in the often uncontrolled process of settlement in coastal lowland. The inhabitants of such areas are generally threatened from the land-side by river flooding and from the sea-side by storm surges. In addition increasing pollution of water often endangers their primary source of survival, the marine ecosystem.

When discussing the probable impact of a rising sea level, the time horizon for our considerations should necessarily be fifty to hundred years. One only has to think about the socioeconomic developments in the past hundred years to realize the importance of societal context. In addition to that, sea level rise is only one of the possible consequences of the increasing atmospheric carbon-dioxide concentration. Compared to climate change, however, sea level rise is a clear, direct, and easy to understand threat.

The reaction to climate changes and sea level rise will also depend upon other controversial matters that fight for a place on the political agenda: unequal distribution of natural resources and affluency, deterioration of the natural environment, transboundary pollution, population increase and food strategies, and possibly armed conflicts. Since the time horizon of most politicians is years rather than decades, it seems unlikely that climate and sea level will get high on the agenda.

Although the effects of climate change are uncertain, it is clear that there will be regional differences and that there will be winners and losers. Sea level rise seems to cause mostly losers; only countries without a coastline--and there are remarkably few of those--are not affected directly. It should be stressed that it is a global but not a natural phenomenon; the increasing concentration of carbon dioxide and other greenhouse gases is the result of human activities. Here we have a typical example of external costs, i.e., costs not included in the cost of present fossil fuel burning. And by all standards these costs will not be trivial.

Coastal areas which are presently in dynamic equilibrium will erode as a result of sea level rise because nature will try to restore equilibrium. Ecologically valuable resources such as wetlands, salt marshes, and mangrove areas will probably disappear faster than they develop and sandy beaches will retreat. Where cities, harbours and other kinds of infrastructure have been built, a "natural" restoration of the equilibrium will not be accepted. Technically, it is possible to build and/or raise dikes, construct drainage systems and adjust the infrastructural works to protect the area against a higher sea level. Once this strategy is adopted, vested interests will call for continuation. The same applies to artificial stabilization of the shoreline through sand suppletion or through construction of groins, dams, etc. (Vellinga, 1986). Although diking is a relatively simple operation, it profoundly changes the environment and entails many hydrological and morphological effects (usually undesirable). Embankment makes it necessary to lay out a system of drainage canals and because of the elimination of the beneficial effects of floods it may become necessary to provide irrigation facilities. Existing simple tidal drainage systems will have to be replaced by pump lift drainage. This is very costly in installation and in operation, especially in the humid tropical zone with its high amounts of rainfall. Where pumplift drainage is already applied (in The Netherlands, Italy, Japan, etc.) the required pump capacity will have to be increased.

A sea level rise will increase the hydraulic loading on coastal structures like breakwaters, locks, bridges, water intakes and outlets, etc. The water level of rivers flowing into the sea will rise accordingly; for flat river deltas this is felt far inland. As a result a large number of facilities will have to be reinforced and adjusted to higher water levels.

A change in climate may very well cause shifts in storm/cyclone/tornado tracks, wind fields and wave characteristics. Therefore, the protection level of existing constructions (dikes, dams, dunes, barriers, etc.) will not necessarily decrease linearly with the rising sea level.

The probable consequences of a rising sea level have been discussed more extensively elsewhere (e.g., Barth and Titus, 1984, and Titus, 1986) and need not be repeated here. Time has come to concentrate on response strategies and the resources needed for implementation. The next sections of this paper address the issue from a policy point of view, based on an interdisciplinary approach.

2. Timing

Timing is crucial when coping with the consequences of sea level rise. On the short run one is confronted with the classic problem of decisionmaking under uncertainty: should one act now with the risk of incurring economic costs that later prove to have been unnecessary, or wait for better information with the risk that later actions--should they be necessary--will be more costly. A tentative sequence of actions is shown in Figure 1.

(a) Raising public awareness

Due to the uncertainties connected to natural variations, a change in sea level will not be recognized as a fact by society until there is full evidence from an increasing number of flood disasters and coastal erosion problems, supported by unambiguous monitoring results. Locally varying phenomena (tectonics, subsidence, geomorphological changes to name a few) may disturb the signal-noise relation. The way information is presented and handled may very well influence public awareness (how to manage uncertainty, how inevitable is sea level rise, what is the predictive power of models, etc.). Evidence will probably be recognized after a continuous global rise in sea level of at least 0.10 m.

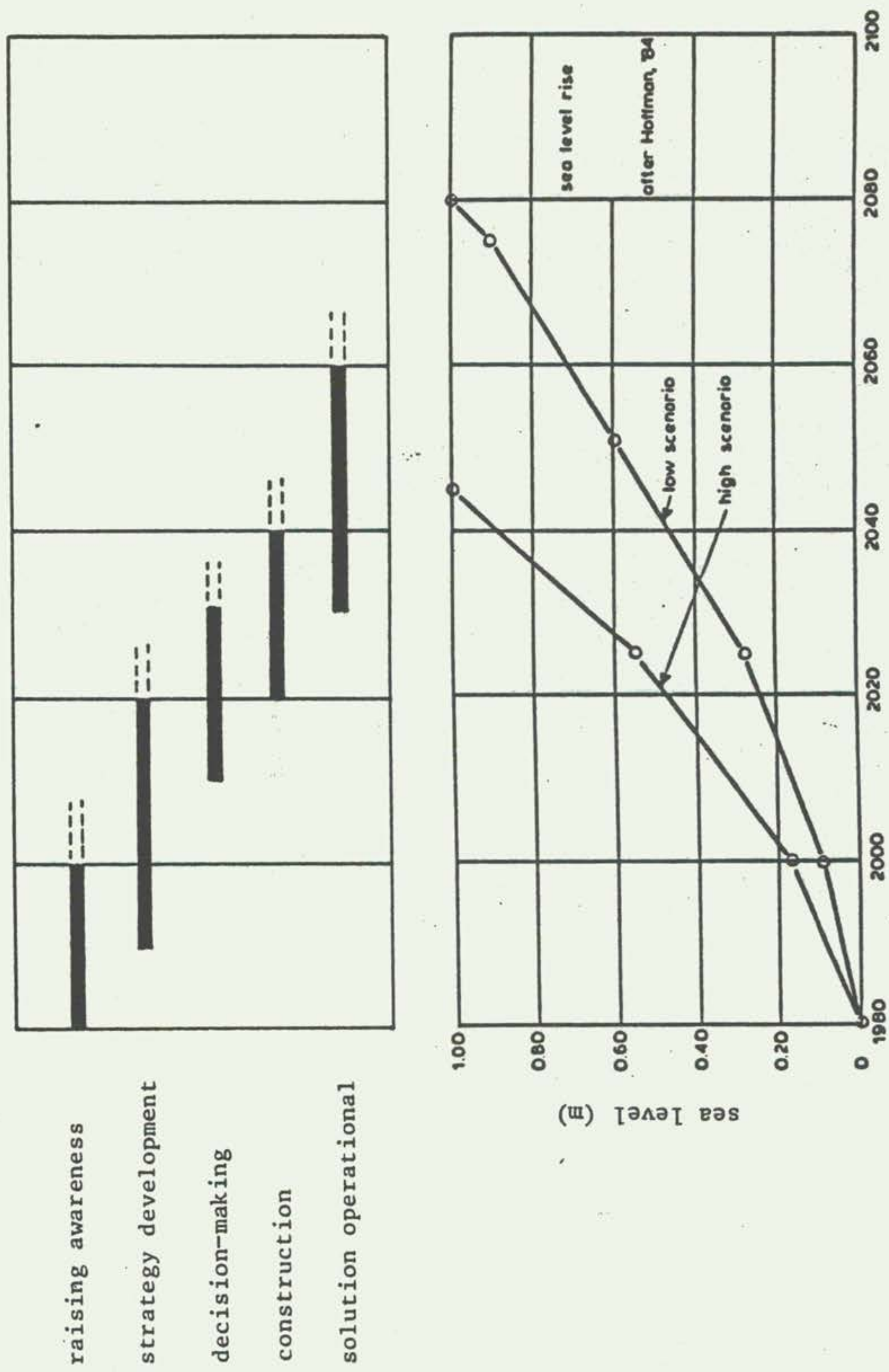

Fig. 1. Time lags in response to sea level rise

(b) Strategy development

The hydraulic and geomorphological coastal processes effected by sea level rise are large-scale processes by nature; consequently, coastal protection schemes must cover large areas to be effective (with inevitable "spillover" effects). Large groups of people will be affected in one way or another. Once the signal is "loud and clear," the question is whether and how to respond. What kind of problem are we really confronted with? How sensitive is the problem to the rate of sea level rise? Various strategies can be adopted, ranging from (selective) retreat to full protection. The availability of technology, manpower, budgetary and other resources will determine which strategies are considered. It should be kept in mind that climate changes will add to the complexity of the problem. Considering all this, it is not overly pessimistic to assume that strategy development will take 10 to 20 years after sea level rise has been recognized as a fact.

(c) Decisionmaking

The recent past has taught us that decisionmakers only react to discrete events and most hesitantly to slow cumulative developments. The reaction to the acid rain phenomenon is a good example of preventive action taken only after it became clear that the natural system was pushed over a threshold with nonlinear deterioration of the environment (large-scale dying of Central Europe's forests). Especially interesting for the present issue is the fact that a real long-term protection strategy against flooding in The Netherlands was developed only after the disastrous 1953 storm surge (Goemans, 1986). Countries with traumatic experience of previous flood disasters may react very differently from other countries.

Any strategy will have a large economic and social impact, with accompanying questions like: who pays for protective measures, how to compensate for land loss, which government level decides on water management alterations. Legal problems will have to be solved and tax schemes worked out, all contributing to the social (un)-acceptability. Because of the large-scale processes, multilateral cooperation with border countries may be necessary. Evidently, the burden of protection against sea level rise will not be distributed equally over the various coastal countries. No doubt some of these countries will lack the necessary money for costly protection schemes. These losers can be expected to ask for help from the countries responsible for the problem in the first place (the "greenhouse gas emitters"). International consensus building about compensation payments may be a long and tiresome process; much will depend, however, upon the international relations in the next century.

(d) Construction

If it is decided to protect the existing land from inundation, the measures to be taken will most probably be large in scale. It is estimated that a sea level rise of 1.0 m will cost The Netherlands about 10 billion guilders (5 billion U.S. dollars). Heightening the dikes would be done in steps of 0.5 m, each step requiring a minimum of 20 years of construction time for the country as a whole (Goemans, 1986). The decision to protect the land in an incremental way is of course influenced by the projected sea level rise rate on one hand and the resources that can be mobilized on the other hand. Once construction starts, the sea level has already risen considerably; hence, a construction period of at least 10 to 20 years should be taken into account.

The figure shows an enormous time lag between the moment of recognition of sea level rise and the moment a protection strategy is effective. In the end the policymaker may find him/herself confronted with an ever increasing sea level and start the whole cycle again. Unfortunately, time lags in the order of 50 years are way beyond our imaginations, and there is no experience whatsoever with public policymaking processes on such a time scale. Of course, this applies also to the climate change issue in general. Where are the critical periods when something should be done? It is a great challenge for policymakers, policy analysts, engineers and scientists to sensitize people to these kinds of processes.

3. Actions needed

(a) Site-specific case studies

So far the effects of sea level rise, as presented in the various workshops and conferences, have been described generally in a qualitative way. To generate a better understanding of the effects and to increase public awareness, it is now time to generate more quantitative information over a wide variety of impact categories (like economic, ecological, health, social and administrative aspects). Such information can only be obtained from a number of in-depth studies for specific sites; for example:

- a very active delta in the humid tropics
- a more stable delta in the arid regions
- a coral reef protected coastal zone
- a low-lying coastal zone typical for an industrialized region
- a coastal stretch with intensive recreational developments

(b) Global network of scientists and policymakers

Climate change and sea level rise are global issues. Therefore, the intellectual power and experience should be connected in a global network such that creativity is stimulated and knowledge can be exchanged. How do we make sure that certain mechanisms in nature are not overlooked? This is important because we can anticipate only what we can forecast. In the network scientists, engineers and policymakers should be brought together with the aim to guarantee a direct spin-off for the decisionmaking process at a later stage. The network should carry out site-specific case studies and exchange the information by means of workshops. The network should preferably operate under the umbrella of a supranational organization.

(c) Policy exercises

Decisionmaking in a complex issue like sea level rise is not an easy matter. A comprehensive view requires a careful policy analysis, which uses all available knowledge about the relevant social, economic, technical and ecological systems and their interrelations. A sufficiently elaborated consistency model can be used to invent, test and compare various strategies. It is believed that a confrontation of different perspectives will give a better sense of the complexity of the issue. Using the model in a free-form game (a "policy exercise" as introduced by Brewer, 1986) with participation of scientists and policymakers focused on a specific case will improve public knowledge.

(d) Research planning

Monitoring networks on sea level, tides, waves, surges and related climatic parameters should be developed in order to be able to detect unambiguously any variation and to improve estimates of future sea level rise. In addition hydrological, geomorphological and ecological responses to sea level rise should be studied. The results of quantitative local case studies on coastal zone response should be used to generate the most promising research options, to reduce present uncertainties and to compose effective solutions. Presently projected coastal infrastructure and water management facilities should be analyzed with respect to their performance with higher sea levels. All systems should be checked for the possibility of adjustments during their planned lifetime; a new design philosophy may be needed with emphasis on flexibility and even movability.

4. A proposal

The history of The Netherlands is marked by storm surge disasters; presently the country is protected by about 400 km of sea dikes and 200 km of dunes, requiring constant and careful maintenance. If the country would not be protected, more than half of it would be uninhabitable; today more than 8 million people live in that area. Small wonder that the Dutch over the years have developed special expertise in managing their water and have applied this knowledge on similar situations around the world.

Given the prospect of a rising sea level the initiative was taken for a project called "Impact of Sea Level Rise on Society" (ISOS). An international seminar was organized by Delft Hydraulics in August 1986. A number of experts in various fields (physics, engineering, environment, economics, social science, policy analysis) were invited to contribute to a framework showing the impact of sea level rise. A preliminary version of a simulation model was operationalized on a PC and served as a tool for the participants in designing management strategies for three situations: The Netherlands, Bangladesh and The Maldives. The conclusions of the meeting were presented to the Dutch Minister of Transport and Public Works (Delft Hydraulics, 1986).

The ISOS-model is described in a forthcoming report which will be presented to UNEP by the Dutch government on November 11, 1987. The basic structure of the model is outlined in figure 2. For a given impact area developments are influenced exogenously by scenarios for sea level, economic growth; in addition a social discount rate can be chosen. Three different impact subareas can be distinguished to allow for differentiation between urban/industrial, agricultural and environmental functions. The area itself is conceived as a system with interrelated components. As a response to the impacts assessed, strategies can be designed to cope with the negative effects of sea level rise. Two "pure" strategies can be distinguished, each composed of a number of tactics:

(1) Prevent land loss by e.g.

- build and/or improve protection systems (type, dimensions, materials, locations, timing, etc.)
- build and/or improve water management systems (drainage facilities, reduction of salt intrusion, etc).
- infrastructural measures related to navigation and ports

(2) Selective retreat by e.g.

- relocation of human activities in time and space (zoning and land use planning)
- resettlement programs including compensation schemes
- cultivation of "unused" areas and rebuilding of sociotechnical infrastructure

Actual strategies will generally be a mix of the above-mentioned pure strategies. Output of the model is presented at steps in time for various impact categories: population at risk, land and capital losses, security from flooding, water resources damages, shipping and port damages, and the costs of the measures.

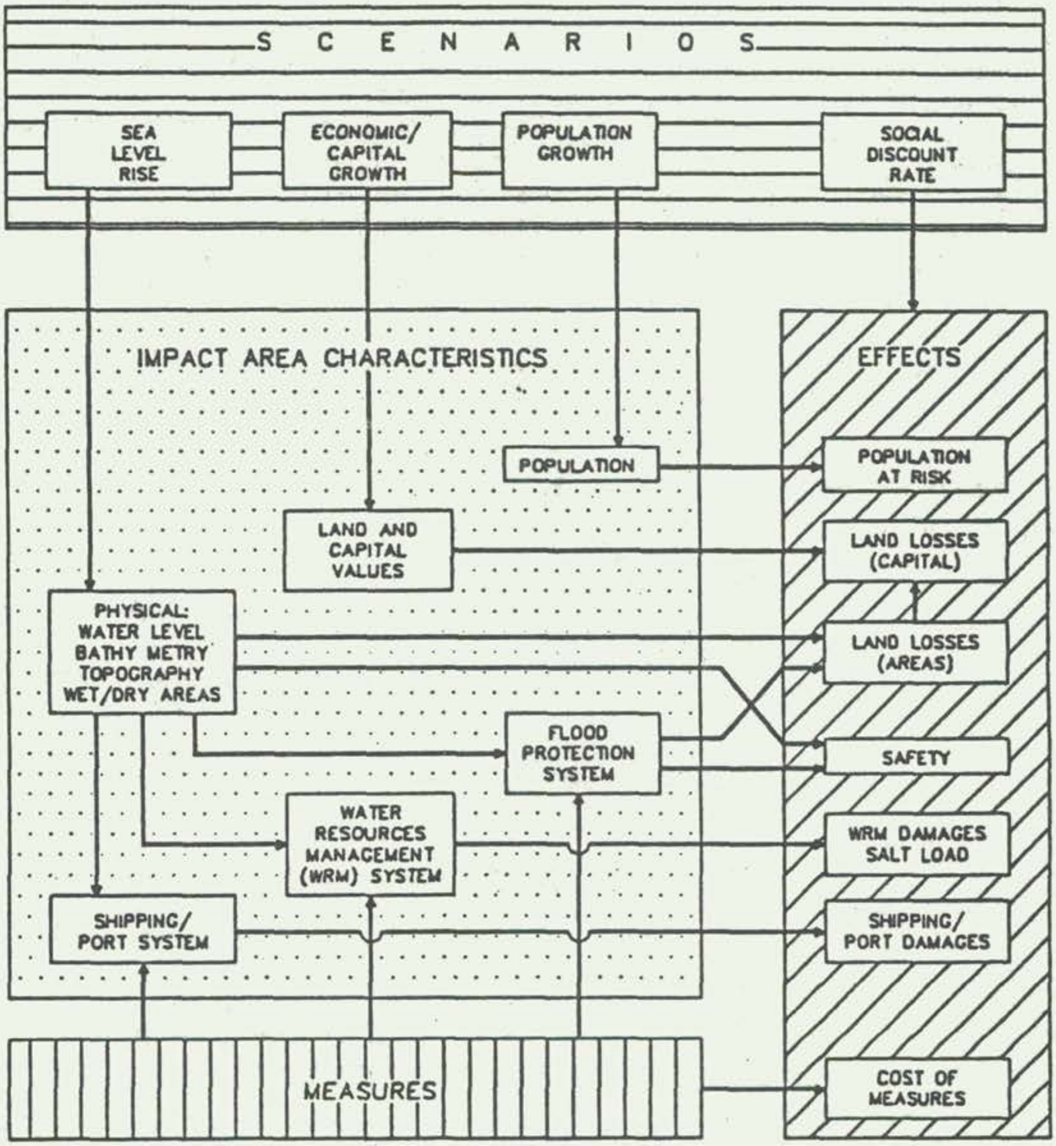

Fig. 2. Simplified system diagram used in the ISOS-model

As a follow-up to this seminar a project proposal has been presented by Delft Hydraulics to UNEP, which includes the following activities:

- building up a global network of expertise in the field of exploring and managing the impact of sea level rise
- develop the ISOS-model into a valuable tool for policy analysis and identify vulnerable areas in the world for potential case studies
- transfer of knowledge about the approach to national planning agencies and conduct policy exercises
- synthesize the results of various case studies in a consistent way and evaluate the progress in regular workshops, thus strengthening the global character of the project and generating more case studies

One of the cases will be The Netherlands in view of the relevance of the sea level issue for this country. Basically, this case study will be sponsored by the Dutch government. Other cases will be selected and funded by UNEP and/or other participating countries. The project will be managed for UNEP by Delft Hydraulics.

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GLOBAL WARMING AND SEA LEVEL RISE: ANTICIPATING THE EFFECTS ON COASTAL STATES

Implications of Sea Level Rise To Coastal Structure Design

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INTRODUCTION

Postulated increase in world temperature as a result of a "greenhouse effect" produced by atmospheric loading of carbon dioxide and trace gases is a tremendous threat to mankind and steps to study and mitigate the potential disaster are a major challenge of the next century. Secondary effects of the potential temperature rise, such as sea level rise, also are important, and both study of potential rises and guidance on responding to sea level rise are important. However, it also is important not to overstate the sea level rise problem or understate uncertainties. Designing coastal projects in response to projected rises of sea level that do not occur within the useful lives of the projects can be as costly as designing at levels that are too low. Quoting the recently completed National Research Council (1987) report, "Construction of almost any conceivable protection against sea level rise can be carried out in a relatively short period of time.

Therefore, if a substantial increase should occur, there will be time to implement protective measures." Thus, the sea level rise hazard faced by coastal states is an economic hazard where the penalty for over-reacting can be as severe as for under-reacting (or even more severe since there is time in the case of underdesign to add protection, whereas there is a permanent economic loss for overdesign).

DISCUSSION

Anticipating the effects of future sea level rise on coastal structures is especially difficult given the very different sea level projections that have been made and their low degree of precision. The Environmental Protection Agency (EPA) study (Hoffman et al., 1983) quoted widely in the popular press predicted a sea level rise of between 0.6 and 3.5 meters by the year 2100 with the most probable rise in the range of 1.5 to 2.1 meters. A National Academy of Sciences (NAS) report published the same year (Revelle, 1983) predicted a rise by 2085 of only 0.7 meters, plus or minus 25 percent. Thus, the NAS report predicted a rise whose upper bound was substantially below the lower bound of the most probable rise predicted by the EPA report and barely within the absolute lower bound of the EPA study. Whether the expected rise is 0.6 or 3.5 meters has tremendous implications for a coastal community. There is a growing consensus (e.g., National Research Council, 1987) that the most probable sea level rise over the next century will be the 0.7 meter estimate of the NAS, and most credible scientists now discount the possibility of a 3.5 meter rise. However, the popular press still cites high levels. For example, a recent Newsweek (June 23, 1986) cited sea level rise up to 3.5 meters and showed maps of flooding that would occur with a 7.5 meter rise (despite the fact that scientists have not predicted a 7.5 meter rise). Even recent scientific literature cites high levels. For example, Oceans (Strickland, 1987) has the statement, "Scientists confidently predict that sea levels will rise one to two meters in the next century." This is approximately 50 to 200 percent greater than the NAS study prediction and implies a degree of certainty that clearly does not exist.

The time phasing of expected sea level rise is critical to plan and design of coastal structures. All predicted sea level rise curves have a concave shape with most of the rise occurring in the second half of the next century. For example, a structure with a 50-year useful life faces a rise of only 27 percent of the full rise of the next century rather than half of the rise (NAS estimate curve). Therefore, structures with a 50-year useful life face only a 0.2 meter eustatic rise over their lifetimes if the NAS estimate is accepted. Of course, local subsidence or rise of land relative to a fixed datum must be superimposed on the eustatic rise. Similarly, a residential structure with a 30-year useful life faces only a 0.1 meter rise and a beachfill with a 10-year life faces less than a 0.02 meter eustatic rise.

What should be the sea level rise scenario used for design of coastal structures? Although the NRC (1987) study accepts the NAS estimate of 0.7 meters in the next century as the most probable eustatic sea level rise scenario, the high degree of uncertainty of sea level rise estimates led to an NRC recommendation that a range of scenarios be used in designing coastal projects. The NRC used scenarios of 0.5, 1.0, and 1.5 meters for the year 2100 to evaluate the design implications of sea level rise. Analogous scenarios (assuming the NAS estimate) that can be used for structures with a 50-year useful life are 0.1, 0.2, and 0.3 meters (of course, local subsidence needs to be added to this eustatic rise). Sensitivity calculations using these specific sea level rise scenarios can be made to aid design decisions. The upper level scenario may well be appropriate for structures ill-suited for retrofitting where a surprise on the up side on sea level rise would require costly changes and thus an initial design that allows for an acceleration of sea level rise is appropriate. It would be appropriate to design for the low level for many coastal structures where the effects of sea level rise can be accommodated during maintenance periods. For example, the height of breakwaters can be raised during maintenance, if required. Typically, breakwaters are expected to settle to a level not known with precision during their useful lives anyway. In addition, breakwaters are typically built in water depths of 5 to 15 meters with design waves of 5 to 10 meters. Eustatic sea level rise of 0.1 to 0.3 meters and corresponding increase in design waves of 0.08 to 0.25 meters are likely within the error bounds of design water levels and wave heights, since the water depths at a structure will vary during the 50-year design life as a result of movements of sediment.

An important conclusion of the recent NRC (1987) study is that, "Sea level change during the design service life (of structures) should be considered along with other factors, but it does not present such essentially new problems as to require new techniques of analysis." Thus, the coastal design approaches developed over the last 50 years are still appropriate for design of coastal structures in an era of rising sea levels. Certainly, the design is complicated by uncertainties of design water levels. The implications of sea level rise can be more readily evaluated in structure design if probabilities reflecting uncertainties are attached to all sea level rise projections. It is incumbent upon investigators predicting sea level rise to develop probability distributions using appropriate statistical techniques, since there is little practical benefit to be gained from projections that cover a substantial range with no analysis of associated probability distributions.

The NRC (1987) study has conclusions and recommendations important to coastal planners and designers. First, "Defensive or mitigative strategies are site specific and cannot be developed nationwide on the basis of a blanket generalization or on comprehensive legislation." Relative sea level rise is not uniform (e.g., locations on the Pacific Coast of the U.S. have falling relative sea level as a result of tectonic uplift of land), and strategies for responding to sea level rise depend upon local conditions (e.g., Is the local coast developed with definite economic benefits to protection or is it an undeveloped coast?). "The prognosis for sea level rise should not be a cause for alarm or complacency. Present decisions should not be based on a particular sea level rise scenario. Rather, those charged with planning or design responsibilities in the coastal zone should be aware of and sensitized to the probabilities of and quantitative uncertainties related to future sea level rise. Options should be kept open to enable the most appropriate response to future changes in the rate of sea level rise." Thus, there are no simplistic answers to how the coastal planner or designer should respond to future potential sea level rise. Decisions will have to be based on a range of scenarios with associated uncertainties clearly factored in and local conditions a key component.

The lack of precision of current world temperature and sea level rise estimates and the large degree of uncertainty make it critical that research in these areas accelerate in the future. There are still very key questions that must be answered for realistic estimates of the impacts of greenhouse warming. One critical area where increased knowledge is essential is the global carbon cycle. A recent article in Science (Kerr, 1986) notes that based upon a state-of-the-art review of the global carbon cycle, "Something is obviously out of whack in the geochemists' models of the carbon cycle, and that could invalidate projections of the amount of carbon dioxide left in the atmosphere to warm the climate of the next century."

Additional research is necessary to accurately establish the timing of carbon dioxide buildup and temperature rise and consequently sea level rise, since design of coastal structures is dependent upon the sea level rise during the useful lives of the structures. The rapid slowdown in fossil fuel consumption worldwide has already moved the projected date of carbon dioxide doubling from as early as 2025 to the end of the next century or beyond (Kerr, 1986). In addition, climate models have generally assumed an instantaneous doubling of carbon dioxide and then determined the resulting equilibrium temperature rise. It is known that transient effects such as the heat storage of the upper ocean will delay any effect for at least decades and these transient effects have not been included in models run to date (Kerr, 1986). Although delays of greenhouse warming by decades will not influence the ultimate impacts of the warming, delays of decades have a profound impact on decisions regarding structures with useful lives of the order of decades. It is clear we will have to depend upon models to project sea level rise since Barnett (1984) shows the large natural variability in sea level will make it ". . . difficult, if not impossible, to detect on realistic time scales" sea level rise acceleration due to man-induced effects. Barnett (1984) indicates gages will require 10 to 100 years to detect sea level rise acceleration.

Research also is needed on how temperature changes will influence sea level. A recent study (Tanner, 1987) cites historical geological evidence that a warmer climate will produce a modest fall in sea level. Presumably, the causal mechanism would be increased snowfall and thus glacier thickness in polar areas as a result of increased temperatures. Whether ice on Antarctica today is shrinking, growing, or in balance is an issue upon which scientists today are deeply divided (Mitchell, 1987). Mass balance studies of the much studied and largest ice drainage system of Antarctica, the Ross Sea system, indicate near steady state on the ice shelf and increasing ice mass for the entire upstream drainage system (Thomas, et al., 1983). Clearly, the relationship between temperature and sea level has not been totally established. In fact, worldwide temperatures particularly in the northern hemisphere fell for almost a fifty year period from the 1930's until the late 1970's, but sea level rose (Barnett, 1982). World temperature rose between 1880 and 1930 (Wallen, 1986), whereas sea level rise showed a slight downward trend (Smith, 1980). Barnett (1982) notes that ". . . a convincing connection between 'global' atmospheric warming and the behavior of the ocean over the last 70-80 years is not easily constructed." The link between carbon dioxide increase and temperature increase also has not been demonstrated empirically. Although climate models predict warming should be occurring particularly in the high latitudes as a result of the carbon dioxide increase in recent years, the CLIMAP (Climate Long-Range Investigation, Mapping, and Prediction) notes, "The Northern Hemisphere, overall but particularly in high latitudes, appears already to be cooling after a century and a half of abnormal warmth" (Mitchell, 1987). In fact, the average temperatures of Winnipeg, Canada, and North Platte, North Dakota, have plunged 5 and 3 degrees Centigrade, respectively, from the 1930's to the late 1970's (Wallen, 1986). The high Great Lake levels in the news in the past few years are due to the unusually low temperatures and high rainfall levels in the U.S. Midwest the last 25 years. Finally, research is needed on the impact that rising temperatures will have on prevailing weather patterns that affect wave generation. In particular, warmer oceans may spawn more powerful and frequent tropical storms. Maximum water levels and wave heights at coastal locations will be governed by this phenomenon rather than increased sea levels.

SUMMARY

The lack of precision and high levels of uncertainty of sea level rise predictions made it difficult in the past to factor sea level rise into coastal structure design. However, the concave shape of predicted sea level rise curves makes predicted rises in the useful life of structures relatively low. The recent NRC study has concluded that current coastal design approaches are still appropriate for design of coastal structures in an era of rising sea level, and a range of sea level rise scenarios over the useful life of the structure should be used in structure design. The large uncertainties in virtually all aspects of the sea level rise issue mandate further research so rational decisions can be made concerning our coastal resources.

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FACTORING SEA LEVEL RISE INTO COASTAL ZONE MANAGEMENT

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If I had to select an issue that should truly challenge the ingenuity of national, state, and local coastal zone management activities in this country, you couldn't find a better one than sea level rise. In fact, if anyone is around in the year 2072 to chronicle the centennial of the Coastal Zone Management Act, they just might use the way we dealt with sea level rise during the last decade of the 20th century as an example of success or failure during the first 100 years of the program.

The implications of sea level rise to the coastal zone manager are relatively straight forward. The two most direct impacts are increased erosion rates and increased inundation from storm surge. Other possible impacts have been recognized such as saline intrusion of ground water and loss of wetlands but erosion and storm surge are the most direct. Coastal zone managers in many states have dealt with these issues and most of us are familiar with the options available as a response. The most common actions are:

- To replenish sand lost by erosion through beach and dune nourishment.
- To armour sections of the coast with seawalls and the like to protect against storm surge.
- And to retreat back from the coast by moving or abandoning structures.

Each of these actions has associated costs and benefits. In general, as the value of property at risk goes up, the costs of armouring or replenishing become more acceptable. As the value of property goes down, the feasibilty of retreat becomes more acceptable. As state and local officials have attempted to develop and implement policies to deal with coastal erosion and inundation from storm surge, they often have had to juggle these several approaches to come up with a mix that is politically acceptable for each state or local area. The two key issues, of course, that make the development of effective policies so difficult are private property rights and the expenditure of public funds.

As I noted, the problems of coastal erosion and storm surge are not new to coastal zone managers. But the spector of sea level rise introduces a new twist that has yet to be addressed in any consistent way around the country. If we agree with the conclusions of the most recent learned studies and reports, those responsible at the state and local level for dealing with the impacts of erosion and storm surge are being told that both the rates of erosion and the frequency and severity of storm surge will increase. And not only that. To the degree that relative sea level rise is caused by a warming of the climate, these increases may accelerate in some nonlinear fashion.

Two factors have made the issue of sea level rise particularly difficult to deal with in the councils of state and local governments where land use policies are made and public funds are allocated. First, uncertainty as to the extent of sea level rise, and, second, the fact that, even under the worst scenerios, the most significant impacts are in the distant future. These two factors are anathema to the political systems charged with making the hard decisions. Nevertheless, I will argue that these two factors -- the distant and uncertain nature of sea level rise -- may allow us to implement general policies now that can evolve as the nature and extent of the problem become better known.

One mechanism that can be used is the National Coastal Zone Management Program and associated state programs. First, a bit of background. The Coastal Zone Management Act of 1972 calls for a partnership between the state and Federal governments to implement a national coastal zone management program. Through this Act, the federal government assists coastal states in developing state coastal zone management programs that meet minimum federal standards. Underpinning the legislation is the recognition by Congress that the coastal states and local governments are where real-world coastal zone management take place. National policy is set by Federal legislation and carried out through individual state plans developed by each participating state and put into play at the state and local level. A good example of Federalism in action. Thirty of the 35 coastal states and territories have voluntarily joined the program.

The Coastal Zone Management Act sets forth basic policies on coastal resources and management philosophy and then spells out some nine performance criteria that must be addressed by each state program to be acceptable. These criteria require state programs to address such issues as the protection of natural resources, beach access, and coastal-dependent uses. It is at the level of these performance criteria that one might consider a requirement for states to specifically address the issue of sea level rise. I should note that states are already tasked to address the general problems of storm surge and coastal erosion. But a requirement for states to specifically consider the unique problems posed by sea level rise does not exist.

The inclusion of a policy on sea level rise in the Coastal Zone Management Act would have two effects. First of all, it would highlight the importance of the issue. Secondly, it would encourage each state to specifically consider the issue in the context of whatever mechanism the state uses to manage and regulate development in its coastal zone. The fact that the potential impacts to people and property are distant and uncertain could be used as an argument to facilitate the implementation now of policies that won't impinge on private property concerns until the distant future when, and if, the significant impacts of sea level rise are felt.

A simple policy statement in a piece of Federal legislation may sound like a mushy bureaucratic way to deal with the implications of sea level rise, but history has demonstrated that states have been very responsive to many of the performance criteria spelled out in the Coastal Zone Management Act. The best example is the requirement for policies on public access to coastal recreation areas. Many states have implemented comprehensive beach access programs, in large part, because it's called for by the Coastal Zone Management Act.

Of course, we aren't starting from scratch. Several states already address some of the managment implications of sea level rise. One approach that may be relatively painless to implement but can account for increased erosion rates and storm surge levels is the moving setback or construction control line. A number of states have setback or construction control lines and they come in many shades and colors.

About one third of the 30 states that have approved coastal zone management programs have established, at least on paper, some form of setback or construction control line. Of the 17 states along the Atlantic and Gulf coast, again, about one third have something on paper. Unfortunately, only a few have put into practice an effective statewide policy for controlling construction in coastal areas subject to erosion and storm surge. The approaches taken by the several states range from a relatively fixed line with limited provision for relocation to a moving setback line based on erosion rates that is recalculated periodically.

Alabama has an example of a fixed construction control line. Criteria used to establish the line included such factors as location of the primary dune system and historical experiences with hurricane overwash. But the line is relatively static and there is no real provision to shift the line in the future based on increased erosion or storm surge due to sea level rise.

On the other hand, North Carolina has in place one of the more effective setback line policies. The key element in North Carolina's approach is the erosion rate which is recalculated for the entire coast every five years. Setback is then calculated on a permit-by-permit basis using the particular erosion rate for the area where the property being permitted is located. In general, for residential structures, the setback is 30 times the annual erosion rate back from the vegetation line; for larger commecial structures, it's 60 times the annual erosion rate back from the vegetation line. These multipliers are considered an approximation of the useful life of the structures involved.

Intellectually, the basis for management strategies such as the North Carolina approach is not sophisticated. Politically, it's down right progressive. You may quibble about the specifics, but the approach can be understood at the local level, and the framework is viable. And the process will evolve. For example, NOAA is currently evaluating proposed changes to the Florida coastal zone management program that establishes a coastal construction line based, in general, on relatively sophisticated mathematical storm surge and erosion models to be updated periodically. In this case we're probing forward with techniques that couple storm surge with erosion rates in a more dynamic mode.

What does the moving setback or construction control line buy you. First, it internalizes changes in erosion rates and storm surge inundation to what specifically happens along the particular coast. Secondly, it can be made relatively painless and conditional on the impact of sea level rise actually happening. Such an approach can be geared to the useful life of the structures involved and the replacement of structures governed by the extent to which the threats materialize. Because we discount into the future, and also into uncertainty, we should be able to put in place policies that will trigger an orderly retreat, where appropriate, should our worst fears be confirmed.

I've dealt here only with the Coastal Zone Management Act as one vehicle for tackling the issue of sea level rise. Other Federal groups, such as the Environmental Protection Agency, the Corps of Engineers, and the Federal Emergency Management Agency, also have mandates and responsibilities and should also factor sea level rise into their policies and practices.

I can visualize our historian in the year 2072. I see him dusting off a yellowing copy of the old National Research Council Report of 1987 and gazing at it with a smile on his face -- not unlike the smile we often have when we read the predictions of 100 years ago. We don't know whether the smile means that we were very prescient back in 1987 or that we widely missed the mark. Then I see him reviewing the evolution of the national coastal zone management effort for the last 13 years of the 20th century. If we've taken the necessary steps, implemented appropriate policies, I'm sure he'll continue smiling. And if by 2072 the actual sea level failed to rise significantly, he'll say thoughtfully, " Smart cookies, those chaps back in the 80's and 90's. They had a high risk problem with high uncertainty. Didn't pan out quite the way they predicted. Didn't have to change coastal development practices very much. But they had good contingency plans." On the other hand, if the sea level rose significantly by 2072, and good contingency plans were in place, he'll simply say, "Smart cookies!"

EFFECTS OF GLOBAL WARMING ON BIOLOGICAL DIVERSITY: AN OVERVIEW

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ABSTRACT

Previous natural climate changes have caused large-scale geographical shifts, changes in species composition, and extinctions among biological communities. If the widely predicted greenhouse effect occurs, communities would respond in similar ways. Moreover, population reduction and habitat destruction due to other human activities would make it difficult for species to shift ranges in response to changing climate conditions. Human encroachment and climate change would jointly threaten many more species than either alone.

Introduction

If the planet warms as projected, natural ecosystems would be stressed by large changes in temperature, moisture patterns, evaporation rates, and other associated chemical and physical changes.

We can infer how the biota might respond by observing the world as it is today. By observing present distributions of plants and animals, which are determined in large part by temperature and moisture patterns, it is possible to hypothesize what would happen if these underlying temperature and moisture patterns changed.

For example, if we know that one race of the dwarf birch, *Betula nana*, can only grow where the temperature never exceeds 22° C (Ford, 1982), then we can hypothesize that it would disappear from those areas where global warming causes temperatures to exceed 22°C.

Ecologists can also observe the results of the many small climate experiments performed by nature every year. We can observe what happens to the birch trees if unusually warm weather occurs during a single year. Perhaps some trees fail to set seed. What happens if there are several warm years in a row? Perhaps some individual trees die.

Also, scientists can look into the past to see how the ranges of plants and animals varied in response to past climate change. A palynologist can count the types of plant pollen found at different depths in the soil, each depth corresponding to the time in which a particular layer of soil was laid down. If birch pollen is found at a depth corresponding to 10,000 years ago, birch trees must have lived in the area at that time.

The fossils of animals convey similar information. If we find tapir and peccary bones in Massachusetts' sediments corresponding to a previous interglacial period of warming, as has been done (Dorf, 1976), we can infer from the presence of the bones that regional temperatures were then higher in Massachusetts. Better indications can be gotten from the fossil bones of small mammals, like rodents, which generally spend their lives within a small area and therefore match the local habitat very well.

These kinds of observations tell us that plants and animals are very sensitive to climate. Their ranges move when the climate patterns change -- species die out in areas where they were once found and colonize new areas where the climate becomes newly suitable. We also know from the fossil record that some species have become completely extinct because they were unable to find suitable habitat when climate change made their old homes unlivable.

As I will discuss below, there will be many ways in which climate change will stress and change natural ecosystems. If warming occurs as projected, during the next 50 years it is likely to change the ranges of many species, disrupt natural communities, and contribute to the extinction of species.

The Nature of the Ecologically Significant Changes

As has been presented at this meeting, there is widespread consensus that global warming will occur during the next century, and that a global warming of $3^{o}C$ may be reached during the next 50 years (Hansen et al. 1981; NRC, 1983; Schneider and Londer, 1984). Ecologically significant temperature rise would occur during the transitional warming phase, well before $3^{o}C$ is reached -- as discussed below, warming of less than $1^{o}C$ may have substantial ecological effects.

For the purpose of discussion in this paper, I will take average global warming to be $3\ ^{o}C$, but it must be recognized that additional warming well beyond $3^{o}C$ may be reached during the next century if the production of anthropogenic greenhouse gases continues.

The threats to natural systems are serious for the following reasons. First, three degrees of warming would present natural systems with a warmer world than has been experienced in the past 100,000 years (Schneider and Londer, 1984). This warming would not only be large compared to recent natural fluctuations, but it would be very fast, perhaps an order of magnitude faster than past natural changes. For reasons discussed in detail below, such a rate of change may prove more than many species can adapt to. Moreover, human encroachment -- habitat destruction -- will make wild populations small and vulnerable to local climate changes.

Second, as presented elsewhere in this conference, ecological stress would not be caused by temperature rise alone. Changes in global temperature patterns would trigger widespread alterations in rainfall patterns (Hansen et al. 1981; Kellogg and Schware, 1981; Manabe et al. 1981; Wigley et al. 1980), and we know that for many species precipitation is a more important determinant of survival than temperature per se. Some regions would see dramatic increases in rainfall, and others would lose their present vegetation because of drought. For example, Kellogg and Schware (1981), drawing on knowledge of past vegetation patterns, project substantial decreases in rainfall in America's Great Plains -- perhaps as much as 40% by the early decades of the next century (Fig. 1b).

Other environmental factors would change because of global warming: Soil chemistry would change (Kellison and Weir, 1986). Increased carbon dioxide concentrations may accelerate the growth of some plants at the expense of others (NRC 1983; Strain and Bazzaz, 1983), possibly destabilizing natural ecosystems. And rises in sea-level may inundate coastal biological communities (NRC, 1983; Hansen et al. 1981; Hoffman, Keyes, and Titus, 1983; Titus et al. 1985). What all this means is that the ranges of individual species would shift and that ecological systems would be disrupted.

One important pattern of global warming, generally concluded by a variety of computer projections, is that warming will be relatively greater at higher latitudes. See, for example, Figure 1a (Hansen et al. 1987). This suggests that, although tropical systems may be more diverse and are currently under great threat because of habitat destruction, temperate zone and arctic species may ultimately be in greater jeopardy from climate change. The second paper in this panel, by Dr. Sylvia Edlund, suggests some of the widespread changes that warming might cause in arctic vegetation. Also, a recent attempt to map climate-induced changes in world biotic communities projects that high altitude communities would be particularly stressed (Emanuel et al. 1985). Boreal forest, for example, was projected to decrease by 37% in response to warming of $3^{o}C$.

How Do Species Respond to Warming?

We know that when temperature and rainfall patterns change, species ranges change. Even very small temperature changes of less than one degree within this century have been observed to

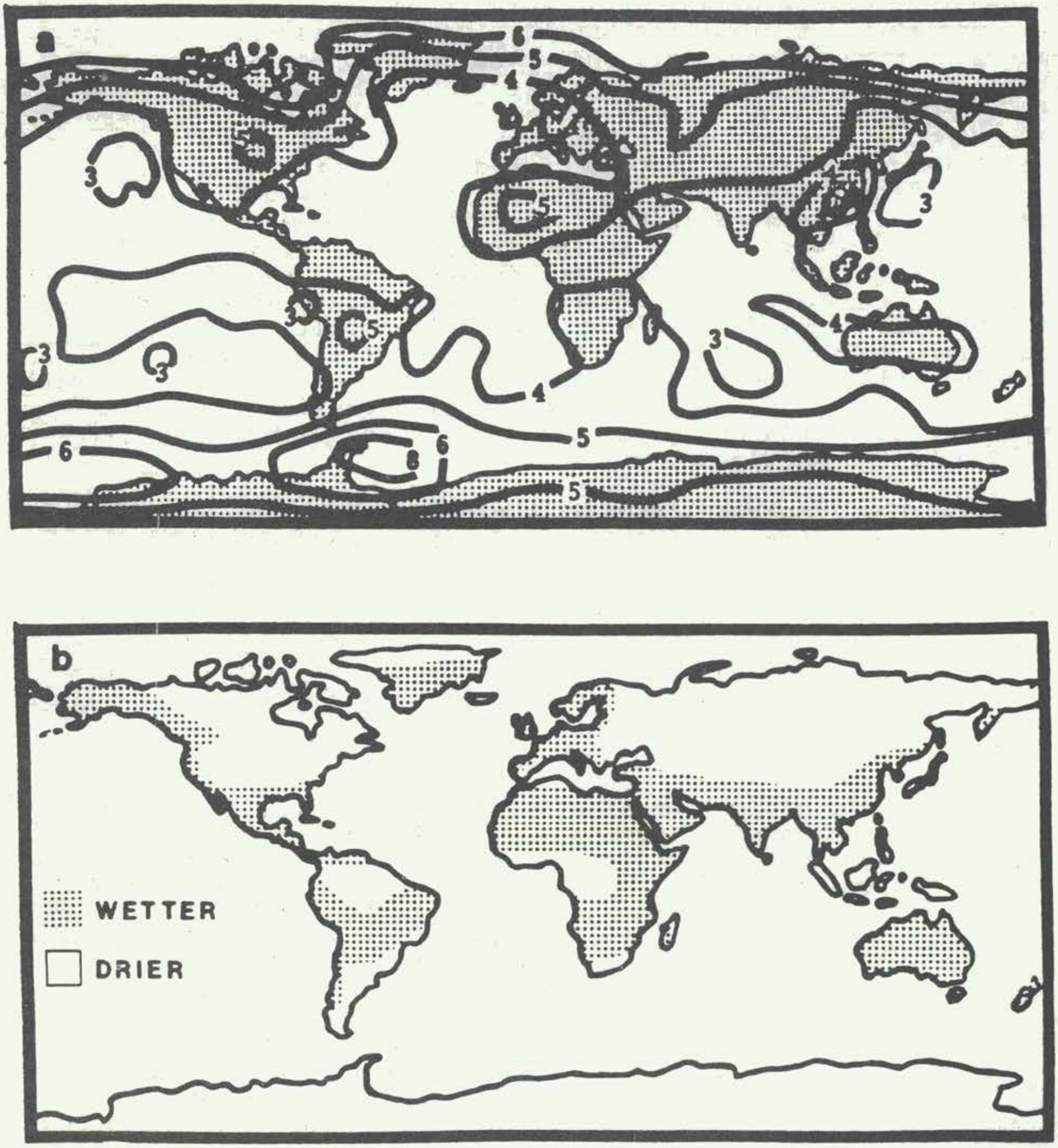

Figure 1. (a) Global patterns of surface temperature increase, as projected by the Goddard Institute for Space Studies (GISS) model (Hansen et al. 1987) in degrees C. (b) Global changes in moisture patterns (Kellogg and Schware 1981).

cause substantial range changes. For example, the white admiral butterfly (Ladoga camilla) and the comma butterfly (Polygonia c-album) greatly expanded their ranges in the British Isles during the past century as the climate warmed approximately 0.5°C (see in Ford, 1982). At the same time, other species that depend upon cooler conditions, like the ant Formica lugubris, retracted their ranges into the cooler uplands.

On a larger ecological and temporal scale, entire vegetation types have shifted in response to past temperature changes no larger than those that may occur during the next 100 years or less (Baker 1983; Bernabo and Webb, 1977; Butzer, 1980; Flohn, 1979; Muller, 1979; Van Devender and Spaulding, 1979). Such shifts show general patterns. As the Earth warms, species tend to shift to higher latitudes and altitudes. From a simplified point of view, rising temperatures have caused species to colonize new habitats toward the poles, often while their ranges contracted away from the equator as conditions there became unsuitable.

During several Pleistocene interglacials, for example, the temperature in North America was apparently 2° to 3°C higher than now. Osage oranges and pawpaws grew near Toronto, several hundred kilometers north of their present distribution; manatees swam in New Jersey; tapirs and peccaries foraged in North Carolina (Dorf, 1976). Other significant changes in species ranges have been caused by altered precipitation accompanying past global warming, including expansion of prairie in the American Midwest during a global warming episode approximately 7,000 years ago (Bernabo and Webb, 1977).

It should not be imagined, because species tend to shift in the same general direction, that existing biological communities move in synchrony. Conversely, because species shift at different rates in response to climate change, communities often disassociate into their component species (Figure 2). Recent studies of fossil packrat (Neotoma spp.) middens in the southwestern United States show that during the wetter, moderate climate of 22,000-12,000 years ago, there was not a concerted shift of communities. Instead, species responded individually to climatic change, forming stable, but by present-day standards, unusual assemblages of plants and animals (Van Devender and Spaulding, 1979). In eastern North America, too, post-glacial communities were often ephemeral associations of species, changing as individual ranges changed (Davis, 1983).

A final aspect of species response is that species may shift altitudinally as well as latitudinally. When climate warms, species shift upward. Generally, a short climb in altitude corresponds to a major shift in latitude: the 3° C cooling of 500 meters in elevation equals roughly 250 kilometers in latitude (MacArthur, 1972). Thus, during the middle Holocene, when temperatures in eastern North America were 2°C warmer than at present, hemlock (Tsuga canadensis) and white pine (Pinus

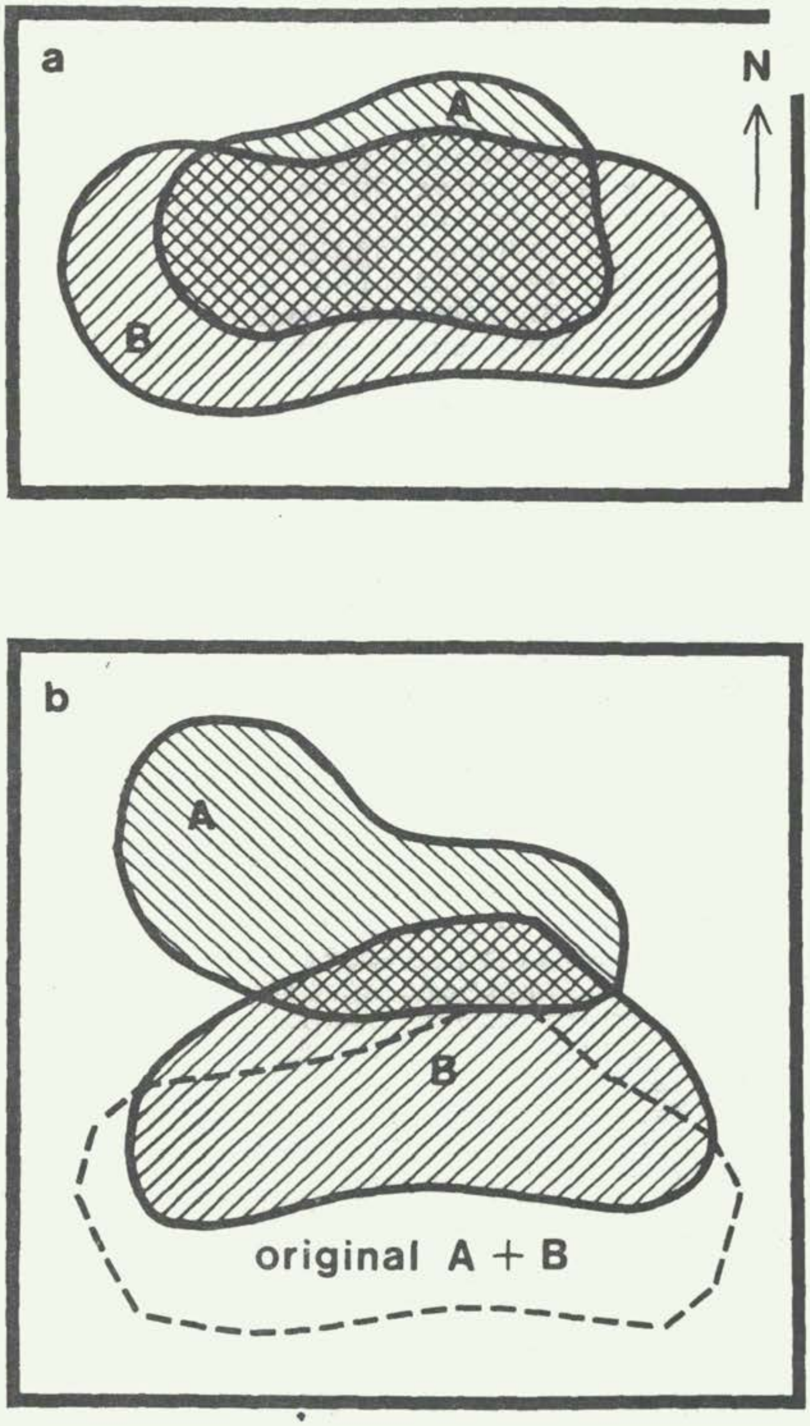

Figure 2. (a) Initial distribution of two species, A and B, whose ranges largely overlap. (b) In response to climate change, latitudinal shifting occurs at species-specific rates, and the ranges disassociate.

strobus) were found 350 meters higher on mountains than they are today (Davis, 1983).

Because mountain peaks are smaller than bases, as species shift upward in response to warming, they typically occupy smaller and smaller areas, have smaller populations, and may thus become more vulnerable to genetic and environmental pressures. Species originally situated near mountaintops might have no habitat to move up to and may be entirely replaced by the relatively thermophilous species moving up from below (Figure 3). Examples of past extinctions attributed to upward shifting include alpine plants once living on mountains in Central and South America, where vegetation zones have shifted upward by 1000-1500 m since the last glacial maximum (Flenley 1979; Heusser 1974).

Magnitude of Projected Latitudinal Shifts

Although Pleistocene and past Holocene warming periods were probably not due to elevated CO_2 levels, researchers have predicted that, if the proposed CO_2-induced warming occurs, similar species shifts would also occur, and vegetation belts would move hundreds of kilometers toward the poles (Frye, 1983; Peters and Darling, 1985). 300 kilometers of shifting in the temperate zone is a reasonable estimate for a 3^oC warming, based on the positions of vegetation zones during analogous warming periods in the past (Dorf, 1976; Furley et al. 1983).

Additional confirmation that shifts of this magnitude may occur comes from attempts to project future range shifts for some species by looking at their ecological requirements. For example, the forest industry is concerned about the future of commercially valuable North American species, like the loblolly pine (Pinus taeda L.). This species is limited to the south of its range by moisture stress on seedlings. Based on these physiological requirements for temperature and moisture, Miller, Dougherty and Switzer (1987) projected a range retraction to the north of approximately 350 kilometers in response to a global warming of 3^oC.

Dispersal Rates and Barriers

The ability of species to adapt to changing conditions will to large extent depend upon their ability to track shifting climatic optima by dispersing colonists. In the case of warming, a North American species, for example, would most likely need to establish colonists to the north. Survival of plants and animals would therefore depend either upon long-distance dispersal of colonists, such as seeds or migrating animals, or upon rapid iterative colonization of nearby habitat until long-distance shifting is accomplished. If a species' intrinsic dispersal rate is low, or if barriers to dispersal are present, extinction may

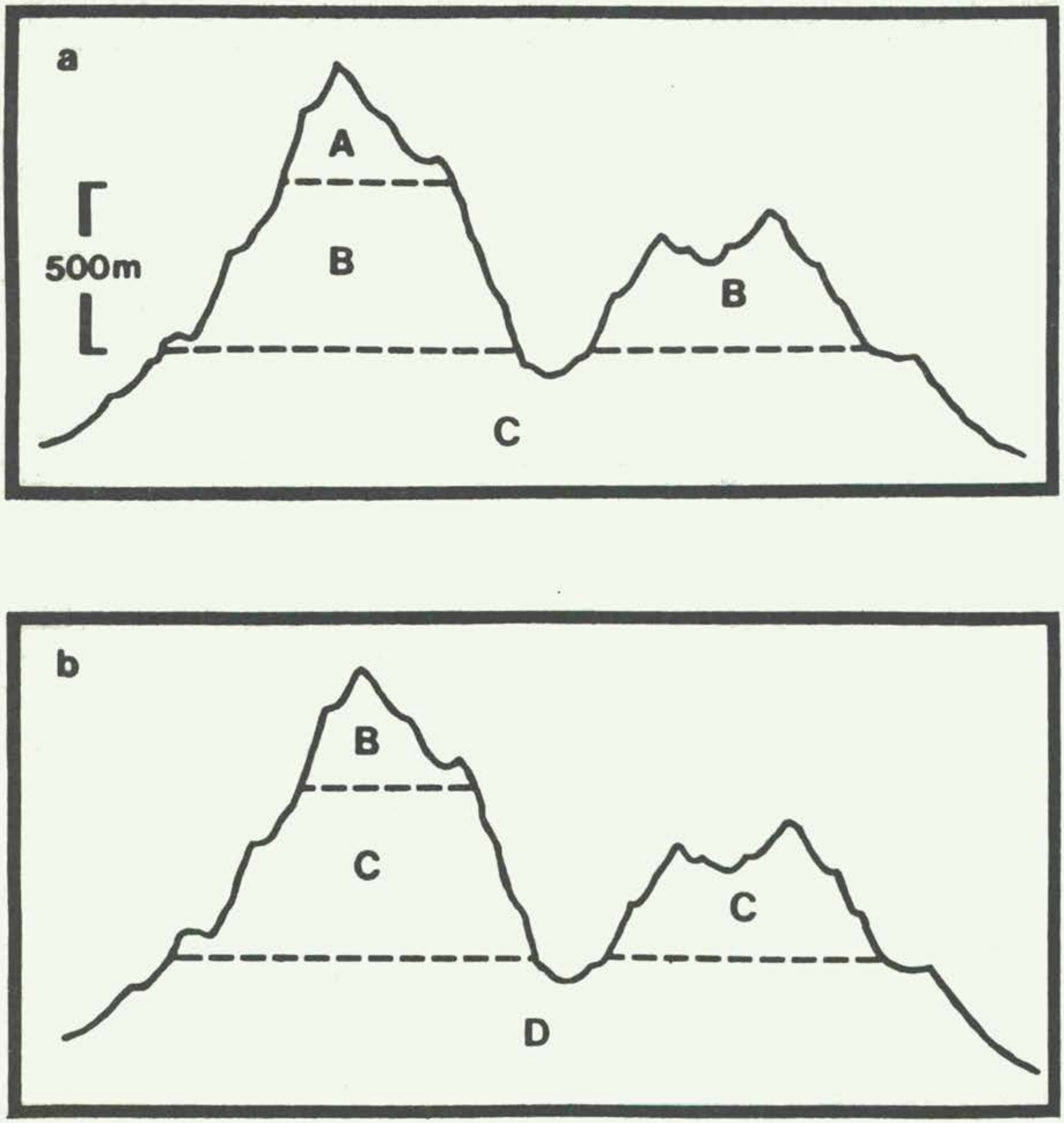

Figure 3. (a) Initial altitudinal distribution of three species, A, B, C. (b) Species distribution after a 500 m shift in altitude in response to a 3°C rise in temperature (based on Hopkin's bioclimatic law; MacArthur 1972). Species A becomes locally extinct. Species B shifts upward, and the total area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

result.

There are many cases where complete or local extinction has occurred because species were unable to disperse rapidly enough when climate changed. For example, a large, diverse group of plant genera, including water-shield (Brassenia), sweet gum (Liquidambar), tulip tree (Liriodendron), magnolia (Magnolia), moonseed (Menispermum), hemlock (Tsuga), arbor vitae (Thuja), and white cedar (Chamaecyparis), had a circumpolar distribution in the Tertiary. But during the Pleistocene ice ages, all went extinct in Europe while surviving in North America. Presumably, the east-west orientation of such barriers as the Pyrennes, Alps, and the Mediterranean, which blocked southward migration, was partly responsible for their extinction (Tralau 1973).

Other species thrived in Europe during the cold periods, but could not survive conditions in postglacial forests. Some were unable to extend their ranges northward in time and became extinct except in cold, mountaintop refugia (Seddon 1971).

These natural changes were comparably slow: Change to warmer conditions at the end of the last ice age spanned several thousand years, yet is considered rapid by natural standards (Davis 1983). We can deduce that, if such a slow change was too fast for many species to adapt to, the projected warming -- perhaps 10 times faster -- will have more severe consequences. For widespread, abundant species, like the loblolly pine modelled by Miller, Dougherty, and Switzer (1987), even substantial range retraction might pose little threat of extinction; but rare, localized species, whose entire ranges might become unsuitable, would be threatened unless dispersal and colonization were successful.

Could an average species successfully disperse given what we know about dispersal rates and barriers? If the climatic optima of temperate zone species do shift hundreds of miles toward the poles within the next 100 years, then these species would have to colonize very rapidly. A localized species might have to shift poleward at several hundred kilometers per century, or faster, in order to avoid being left behind in areas too warm for survival. Although some species, such as plants propagated by spores or dust seeds, may be able to match these rates (Perring 1965), many species could not disperse fast enough to compensate for the expected climatic change without human assistance (see in Rapoport, 1982), particularly given the presence of dispersal barriers. Even wind-assisted dispersal may fall short of the mark for many species. For example, wind scatters seeds of the grass Agrostis hiemalis, but 95% fall within 9 m of the parent plant (Willson, 1983). In the case of the Engelmann spruce, a tree with light, wind-dispersed seeds, fewer than 5% of seeds travel even 200 m downwind, leading to an estimated migration rate of between 1 and 20 km per century (Seddon 1971).

Figure 4 illustrates the difficulties to be faced by a population whose habitat becomes unsuitable due to climate change. Colonists (e.g. seeds) must run an obstacle course through various natural and human-created dispersal barriers in a limited amount of time in order to reach habitat that will be suitable under the new climatic regime. For the example selected, with a dispersal rate of 20 kms per century, successful dispersal is highly improbable.

Although many animals may be, in theory, highly mobile, the distribution of some is limited by the distributions of particular plants; their dispersal rates may therefore largely be determined by those of co-occuring plants. Behavior may also restrict dispersal even of animals physically capable of large movements. Dispersal rates below 2.0 km/year have been measured for several species of deer (Rapoport, 1982), and many tropical deep-forest birds simply do not cross even very small unforested areas (Diamond 1975). On the other hand, some highly mobile animals, particularly those whose choice of habitat is relatively unrestrictive, may shift rapidly. Several authors (see Edgell 1984) have suggested, for instance, that climate change caused major range shifts in some European migratory waterfowl in this century.

Even if animals are good dispersers, suitable habitat may be reduced under changing climatic conditions. For example, it has been suggested that tundra nesting habitat for migratory shore birds might be reduced by high-arctic warming (Myers, 1988).

Synergy of Habitat Destruction and Climate Change

We know that even slow, natural climate change caused species to become extinct. What is likely to happen given the environmental conditions of the coming century?

Some clear implications for conservation follow from the preceding discussion of dispersal rates. Any factor that would decrease the probability that a species could successfully colonize new habitat would increase the probability of extinction.

Thus, species are more likely to become extinct if their remaining populations are small. Smaller populations mean fewer colonists can be sent out and that the probability of successful colonization is smaller.

Species are more likely to become extinct if they occupy a small geographic range. It is less likely that some part of their range will remain suitable when climate changes. Further, if a species has lost much of its range because of some other factor, like habitat destruction, it is possible that the remaining populations are not located in prime habitat -- they might now be found in that part of their historic range which is most susceptible to climate change.

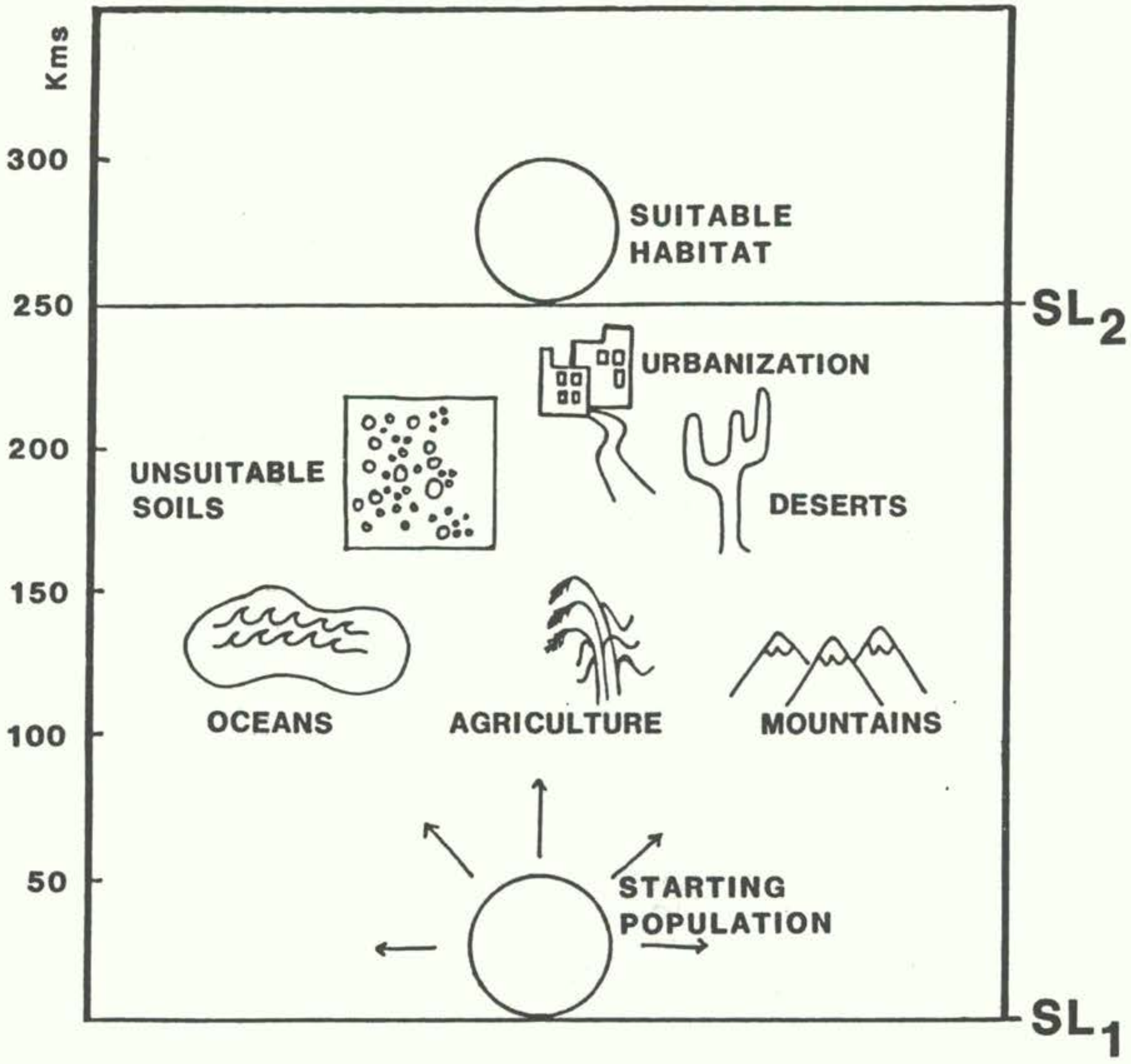

Figure 4. Obstacle course to be run by species facing climatic change in a human-altered environment. To "win," a population must track its shifting climatic optimum and reach suitable habitat north of the new southern limit of the species range. SL1 = species southern range limit under initial conditions. SL2 = southern limit after climate change. The model assumes a plant species consisting of a single population, which has its distribution determined solely by temperature. After a 3°C rise in temperature the population must have shifted 250 km to the north to survive, based on Hopkins bioclimatic law (MacArthur 1972). Shifting will occur by simultaneous range contraction from the south and expansion by dispersion and colonization to the north. Progressive shifting depends upon propagules that can find suitable habitat to mature and in turn produce propagules that can colonize more habitat to the north. Propagules must pass around natural and artificial obstacles like mountains, lakes, cities, and farm fields. The Englemann spruce has an estimated, unimpeded dispersal rate of 20 km/100 years (Seddon 1971). Therefore, for this species to "win," colonizing habitat to the north of the shifted hypothetical limit would require a minimum of 1,250 years.

As previously described, species are more likely to become extinct if there are physical barriers to the colonization, such as oceans, mountains, and cities (Fig. 4).

For many species, all of these conditions will be met by human-caused habitat destruction, which increasingly confines the natural biota to small patches of original habitat, patches isolated by vast areas of human-dominated urban or agricultural lands. This problem by itself threatens hundreds of thousands of plant and animal species with extinction within the next 20 years (Myers, 1979; Lovejoy, 1980).

Habitat destruction in conjunction with climate change sets the stage for an even larger wave of extinction than previously imagined, based upon consideration of human encroachment alone. Small, remnant populations of most species, surrounded by cities, roads, reservoirs, and farm land, would have little chance of reaching new habitat if climate change makes the old unsuitable. Few animals or plants would be able to cross Los Angeles on the way to the promised land. Figure 5 illustrates the combined effects of habitat loss and warming on a hypothetical reserve.

What This Means For Management

There is not space to detail management options in this paper. See Peters and Darling (1985) for a further discussion. In brief, however, there are possible strategies to mitigate species loss. Better characterization of future regional climatic regimes is vital. Such information could be used to make better decisions about siting or modifying reserves. Corridors, for example, particularly in mountainous regions where dispersal distances need not be large, could provide avenues for dispersal. Similarly, managers of coastal marshes might wish to ensure that uplands are conserved in anticipation of when rising sea level forces marshes upward. Forewarning of local environmental trends might also allow reserve managers to prepare for active management of reserve conditions, as by irrigating to compensate for decreased rainfall.

The most comprehensive conclusion, however, is that because species with fragmented populations and reduced ranges are so vulnerable to climate change, one of the best things that can be done now is to minimize further range reduction. Thus, climate change is a compelling new reason to conserve as many natural lands as possible.

Conclusion

Finally, not all the changes for wild systems would be negative. Some species would expand their ranges and have greater abundances. It has been suggested, for example, that

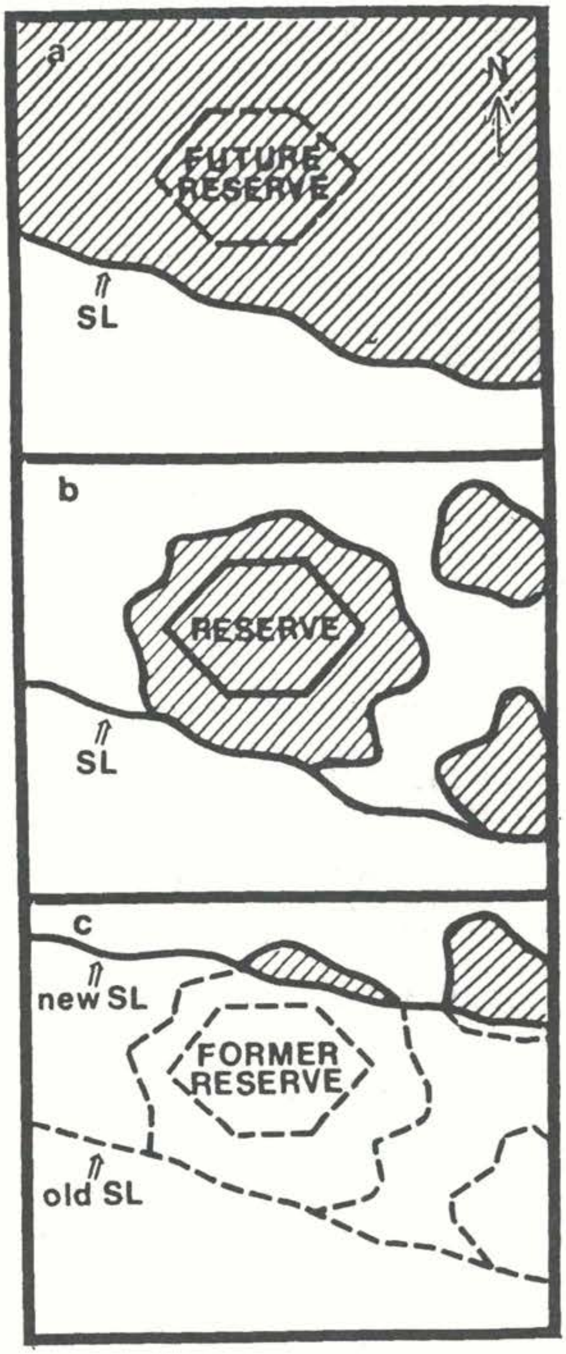

Figure 5. How climatic warming may turn biological reserves into former reserves. Hatching indicates: (a) species distribution before human habitation, southern limit, SL, indicates southern limit of species range; (b) fragmented species distribution after human habitation; (c) species distribution after warming.

some arctic-nesting waterfowl might expand their populations as conditions warm (Harington, 1986).

However, the most optimistic thing that should be said about the future of natural systems under a regime of warming climate is that a great deal of rearrangement would occur, and it is most likely the outcome will be widespread extinction of species.

Acknowledgments

Please see Peters and Darling (1985) for a complete list of acknowledgments for help with this work. Many of the ideas presented here derive from that paper and from the contributions of Joan Darling.

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EFFECTS OF CLIMATE CHANGE ON DIVERSITY OF VEGETATION IN ARCTIC CANADA

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INTRODUCTION

A common image of the Canadian Arctic is that of a vast, impoverished, fairly homogeneous barrens that covers the northern third of Canada. The Arctic, however, is anything but uniformly barren or homogeneous. Some surficial materials support no plant growth at all, while others are too coarse for rooting plants to grow. But in many areas what may appear as a wasteland to forest-oriented persons contains surprisingly diverse and productive ecosystems that support large herbivore populations.

To understand what effects climate change might have on the arctic vegetation it is necessary to understand the two major factors influencing modern vascular plant diversity and distribution: Geology and Climate. Many species and plant associations have particular preferences and intolerances for chemical, textural and moisture variations of the soils, and climate affects the diversity, density, productivity and growth forms of plant communities on any given type of material by controlling the length and intensity of the thaw season, variations in precipitation and in intensity and duration of cloud cover.

Summer warmth is the climate parameter that has the greatest influence on vegetation diversity (Rannie, 1986). This control is best expressed as summations of total warmth such as Melting Degree Days or Growing Degree Days; however, such data is very limited in the Arctic. The most readily available and widespread measure of summer warmth is mean July temperatures. Mean July isotherms show a broad gradient from south to north in the Canadian Arctic, from roughly 10 degrees Centigrade near treeline, to 1 degree Centigrade along the northwest rim of the Queen Elizabeth Islands. This is not a simple linear progression of a 1 degree Centigrade drop in temperature for each 2 hundred kilometers north. It is instead a complex pattern reflecting the interaction between the topography, origin of the predominant air masses and the proximity of sea ice or open water (Edlund, 1986).

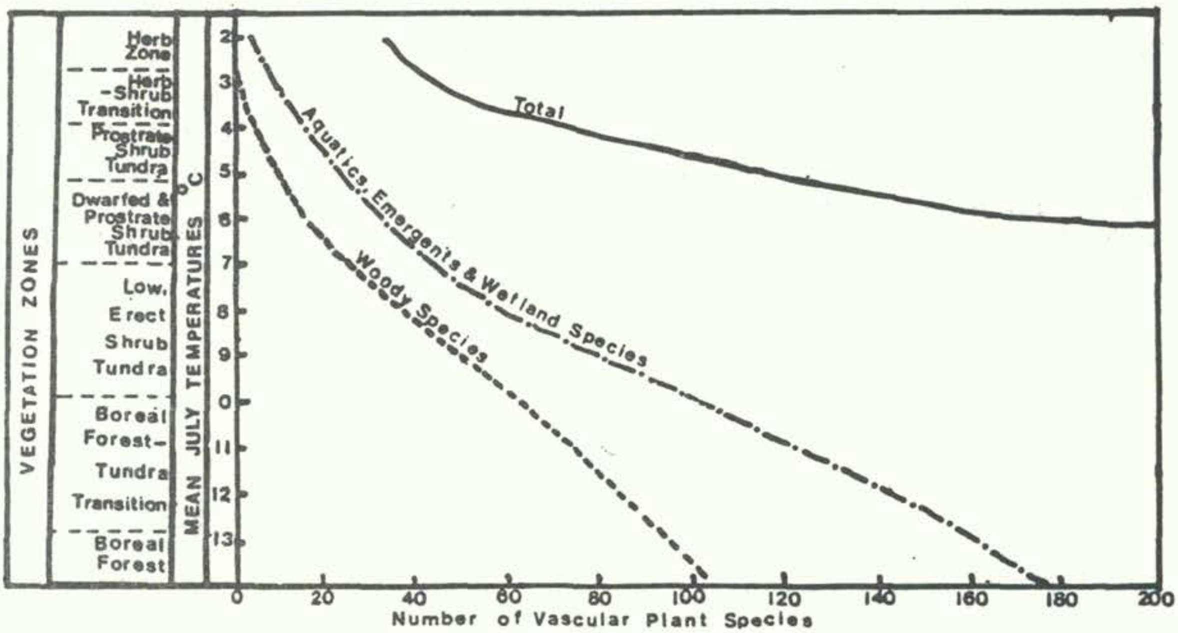
Mean July temperatures vary from year to year, with almost as much variation (1.5 to 2.5 degrees Centigrade) as is predicted for a warming due to increased carbon dioxide. It is, however, the frequency and intensity of warm temperatures that may change with climatic change. New temperature means will become established.

Once mapping of plant associations has been completed for a large area of Arctic Canada and broad vegetation patterns that evolved from the mapping were compared to summer climate patterns, a link evolved between major vegetation pattern changes and several mean July isotherms (Edlund, 1983; 1986; 1987). This resulted in the delineation of seven major bioclimatic zones. These zones, named after the dominant vascular plants, can be bracketed by mean July temperatures which reflect roughly coincident isotherms. These are not to be interpreted directly as physiologically significant temperatures, but rather as relative indicators of regional warmth.

BIOCLIMATIC ZONES IN ARCTIC CANADA

Diversity decreases dramatically through the zones with decreasing summer temperatures (Fig. 1). The diversity of both wood species and of species associated with wetlands and pond environments sharply drops, particularly at temperatures below 7 degrees Centigrade, while total diversity shows a more gradual drop. Perennial herbaceous species make up the largest number of taxa in all zones. Annuals are rare in the Arctic, and biennials are few and generally restricted to the warmest zones.

DIVERSITY OF VASCULAR PLANTS



Seven major bioclimatic zones represent major shifts in vegetation patterns with increasingly severe summers:

BOREAL FOREST

The northern limit of the continuous boreal forest, which also coincides with the southernmost extent of the arctic biome, is one of the best known bioclimatic markers. It roughly coincides with the mean position of the Arctic front in summer (Bryson, 1967) and also with the 13 degree Centigrade mean July isotherm (Hare, 1970). Diversity is greatest within this zone: over 500 vascular plants occur near the northern limit of the boreal forest, including 100 woody species and 170 wetland, aquatic and emergent species (Porsild and Cody, 1980).

FOREST-TUNDRA TRANSITION

Below 13 degrees Centigrade mean July temperatures the tree growth form is no longer dominant; however, woody plants continue to dominate all but the wettest terrain. The latter is vegetated by a variety of sedges and grasses. Between 13 and 12 degrees Centigrade trees are commonly found in an open formation; between 12 and 10 degrees Centigrade trees are generally restricted to favoured locations such as sheltered sunny slopes and well-watered valley bottoms. Low, erect shrubs are the dominant vascular plants on all but the shallowest soils and most exposed terrain. Prostrate (low and sprawling) shrubs are more common on more exposed sites. Tree-sized deciduous shrubs such as paper birch, willow and alder may occur locally in this zone. The total vascular plant diversity is greater than 400 species, including 75 woody species, and 133 wetland, aquatic and emergent species.

Treeline, the northern limit of the coniferous tree growth form, roughly coincides with the 10 degree Centigrade mean July isotherm (Hare, 1970). This also roughly marks the northern limit for many other more temperate shrubs including northern rose, bog laurel, bay, spirea, soapberry, common Labrador tea and common bearberry.

LOW, ERECT SHRUB TUNDRA

North of treeline lies a region with mean July temperatures of roughly 10 to 7 degrees Centigrade which corresponds to the best vegetated arctic areas. Conifers are absent, except near treeline, where they may locally occur in a severely dwarfed, or "krummholz" form. Woody plants, particularly low, erect shrubs such as dwarf birch, willows and heaths are dominant. In the warmest sector the low shrub thicket canopy is nearly continuous; in cooler sectors, dense shrub thickets are restricted to more sheltered locations.

Within this zone there are local occurrences of tree-sized deciduous shrubs such as the felt leaf willow. This tall growth form generally occurs on floodplains near the edge of a deep channel. Away from the stream edge the same willow species adopts the more traditional low, erect growth form (Edlund and Egginton, 1984).

Diversity in this zone ranges from 300 to 400 vascular plant species including 49 woody species, and 75 wetland, aquatic and emergent species. This zone marks the northern limit of many common shrub species such as dwarf birch, northern Labrador tea, and crowberry.

DWARFED AND PROSTRATE SHRUB TUNDRA

Between 7 and 5.5 degrees Centigrade mean July temperatures the low, erect growth form of numerous shrub species is absent, although the species capable of this growth form are still present. This zone is dominated by shrubs that are genetically dwarfed such as arctic willow and arctic avens, while the dwarfed shrubs make up only a small component in sheltered, well-watered locations. Vascular plant species diversity ranges from 150 to 300 species, including 17 woody species and 35 wetland, aquatic and emergent species.

PROSTRATE SHRUB TUNDRA

Between 6 and 4 degrees Centigrade mean July temperatures woody species still persist as dominants, but the taxa are restricted to shrubs that do not have the capacity for erect growth, such as arctic willow and arctic avens. Heath species are greatly restricted to the most sheltered and warmest regions of the zone. Arctic heather, the hardiest heath species, rarely occurs where mean July temperatures are less than 5 degrees Centigrade. Diversity within this zone ranges from 75 to 150 vascular plant species, including only 12 woody species and 24 wetland, aquatic and emergent species.

The 4 degree Centigrade mean July isotherm coincides with the northern limit of woody plant dominance, and may be considered a "mini-forest" limit. It also coincides with the northern limit of sedge dominance in wetlands.

PROSTRATE SHRUB-HERB TRANSITION ZONE

Regions with mean July temperatures below 4 degrees Centigrade no longer have shrubs as dominant vascular plant species. Instead herbs, generally those that were common associates in plant communities farther south, dominate. Where mean July temperatures are between 3 and 4 degrees Centigrade, woody species may be locally present, but only in favoured locations. Diversity in this zone ranges from 35 to 75 vascular plant species, including only 2 woody plants and 11 wetland, aquatic and emergent species. Wetlands are dominated by grasses; sedges are quite restricted in distribution. The 3 degree Centigrade mean July isotherm coincides roughly with the northern limit of woody plant species, in effect a "mini-treeline".

HERBACEOUS ZONE

Vascular plant assemblages are entirely herbaceous in regions where mean July temperatures fall below 3 degrees Centigrade. These regions are devoid of woody plants, sedges, members of the Asteraceae, and aquatic species. The total vascular plant diversity is less than 35 species, in some places a single species may grow fairly abundantly in monoculture. No true wetland species occur in this region. Four species grow in saturated soils, but they are species that also occur on somewhat drier habitats as well.

POTENTIAL EFFECTS OF CLIMATIC CHANGE IN ARCTIC CANADA

These links between modern vegetation zones and climate provide a tool to examine the effects of climate change. (A

1 degree Centigrade warming in summer is thought to extend the growing season by about 10 days.) Climatic controls on vegetation are direct, and the responses to small changes can be dramatic. Many species are at their limits of tolerance. Even a half a degree or 1 degree Centigrade warming can make a difference in a plant's survival and reproductive capacity, and thus affects diversity.

A warmer winter, with an increased snowfall could negate some of the effects of a longer or warmer summer, providing the snow accumulation was sufficiently thick to delay the exposure of the ground surface by days to weeks.

IMMEDIATE EFFECTS

Some effects could be immediate. Warmer or longer summers could result in an increase in size and vigour of some perennial species already present in the ecosystem, and there could be a more consistent and successful seed production of almost all species present. Dwarfed species capable of low, erect forms could grow taller, and more dense, as would shorter shrubs in the low, erect shrub tundra zone. Habitats for species with more southerly ranges could become available. However, gains in growth and range extensions may be negated if climate change includes an increase in variability, including severely cold summers.

LONG TERM EFFECTS

A persistent warming trend in Arctic Canada could eventually result in a northward extension of treeline, and those species associated with the Forest-Tundra transition zone, and probably a northward shift of all zones. This, however, could take several hundreds to thousands of years to produce a visible change. Eventually, the Arctic ecosystem could shrink to less than 1/4th of Canada instead of the current 1/3rd. Woody plants could extend and dominate all lands except those at high elevations. Diversity in all arctic regions could ultimately increase, given enough time and readily available seed sources.

A predicted sea level rise accompanying a general global warming would have an initial, detrimental impact on important arctic wildlife habitats, especially those important to migratory waterfowl such as wetlands and lowland assemblages with sedges, emergents and shrubs. Most breeding and staging areas are currently located in lowlands immediately adjacent to the coast. Major portions of these coastal lowland areas could be flooded with less than a meter or two rise in sea level.

PREDICTING FUTURE CHANGES BY UNDERSTANDING PAST CHANGES

One of the best tools for predicting future impacts of climate change in Arctic Canada involves examining what happened to plant distribution during other periods in the Earth's history when there were warm periods. The rough link established between modern vegetation and climate patterns gives the ability to judge the magnitude of climate changes from pollen and plant macrofossil records.

The current distribution of vegetation cover does not reflect the maximum range extension of plants or communities since the last glaciation. Fossil records indicate that the boreal forest limit was 50 to 280 km north of its current position, reflecting an increase of 2 to 3 degrees Centigrade in mean July temperatures. Timing of the maximum extent of forest was not synchronous (Edlund, 1986 summary). It occurred around 9000 to 8000 years ago along the Beaufort Sea coast, 6000 years ago in central Keewatin, and around 5000 years ago in Northern Quebec. The delays seem to reflect the persistence of remnants of Lauentide Ice in the central and eastern continental areas.

Boreal forest retreat started around 8 to 6000 years ago in the west, reached its current position 4500 years ago in the far west, 4000 years ago in Keewatin, and 3000 years ago in Northern Quebec. The forest limit has roughly remained in its current position in modern times; there have been only minor range fluctuations.

Much less is known of the vegetation history in the treeless Arctic, particularly the Arctic Islands. Preliminary studies indicate that low, erect shrub tundra assemblages migrated northward during the climatic optimum, then retreated in synchrony with the retreat of the forest. Richer plant communities occurred in the far north than are reported there today. Fossils of *Potamogeton* and birch, dating 8000 years ago have been found on west central Ellesmere Island, in an area where they do not occur today (Hodgson, 1985). The closest occurrences of these species is at least 500 to 1000 km away. This suggests that temperatures increases of at least 3 to 5 degrees Centigrade may have occurred then.

During the mid-Holocene climatic optimum the 10 degree Centigrade mean July isotherm could have extended well onto the southern Arctic Islands. Spruce and larch theoretically could have grown there, but due to the poor viability of seeds from treeline locations, and the short-distance seed dispersal of the species it may not have been able to migrate over the inner-island channels. Conifers have not been present in the Arctic Islands since the early Pleistocene 700 to 900,000 years ago, even though temperatures that would favour their growth occurred in the southern Arctic Islands during several interglacials and during the most Holocene climatic optimum.

The geographic isolation of the Arctic Islands, coupled with material-controlled barriers such as areas of highly alkaline soils incapable of supporting plants, drastically slow migration of vascular plants. This type of isolation is currently in operation today, for example: a warm zone on west-central Ellesmere Island has temperatures that theoretically could support low, erect shrub species and growth form. However, the region is ringed by inter-island channels, mountains with extensive ice caps and in some places hostile soils. There is no readily available natural way to get more southerly species into this region.

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THE IMPACT OF CHANGING CLIMATE ON SOME VERTEBRATES IN THE CANADIAN ARCTIC

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INTRODUCTION

Great changes in climate and vertebrate life have occurred in the Canadian Arctic based on our knowledge of the geological record. To gain a perspective on the present situation I will briefly review some finds from the past--especially as they relate to prevailing climate of the period. Generally, although detailed study will show much greater complexity, climatic implications derived from the fossils demonstrate a marked climatic cooling from topical in Siluro-Devonian time to arctic in the Quaternary period. In dealing with the present, known distributions of some prominent arctic vertebrates will be considered with emphasis on core areas of range, and some of their climatic controls. Then, consideration will be given to possible future effects on selected vertebrates of: (1) an extreme warming of climate; and (b) extreme cooling of climate.

THE PAST

Silurian-Devonian

Several localities in the central Canadian Arctic Islands (e.g., Somerset, Prince of Wales, Cornwallis islands) have significant fish faunas of Siluro-Devonian (about 400 million years ago) age. For example, armoured, jawless ostracoderms have been reported from the Port Leopold area of Somerset Island (Dineley and Loeffler, 1976). Evidently, they lived about the time red beds, evaporites and reefs were being laid down--indicative of tropical conditions (R. Williams, personal communication, 1986). A much richer ostracoderm fauna has been reported from the Nahanni region of the western mainland Northwest Territories, and it appears that Arctic Canada was an evolutionary centre of certain groups of these fishes.

Cretaceous

Marine reptiles (mosasaurs and plesiosaurs) and loon-like birds (Hesperornis regalis) lived in the lower Anderson River area, Northwest Territories during the late Cretaceous (about 70 million years ago) (Russell, 1967). It is interesting to note that these vertebrates are also known from sites much farther south (e.g., the Niobrara Chalk in western Kansas) about the same time. The presence of plesiosaurs indicates that, at least seasonally, temperatures were high enough to allow large, cold-blooded marine reptiles to inhabit northern regions. A modern climatic analogue might be coastal California or southern England (D.A. Russell, personal communication, 1986).

Tertiary

In the summer of 1975, Mary Dawson and Robert West discovered the first remains of Tertiary Early Eocene (about 55 million years ago) vertebrates near Strathcona Fiord on southwestern Ellesmere Island (Dawson et al., 1976; Hickey et al., 1983). The fossils represented several species of fish, a small alligator, three kinds of turtles, and several mammals including flying lemurs: evidently they occupied a warm temperate climate. However, based on percentages of plant species with entire-margined leaves, and conclusions based on supposed environmental requirements of the vertebrates, a mean annual temperature of 57-59 degrees Fahrenheit (13.8-15 degrees Centigrade) has been estimated--more nearly subtropical than warm temperate (Hickey, 1984)! Hickey speculates further that heat loss during the dark period was retarded by thick blankets of cloud and fog; that the alligators and some of their warm-blooded compatriots may have hibernated; and that some of the mammals could have fed on nuts, seeds, and sub-bark tissue during that period. Later, Dawson made collections of fossils representing a heavily-built rhinoceros, rabbit, chevrotain and fish from a very confined Eocene site in the Haughton Astrobleme on Devon Island. Evidently, the climate was cool-temperate, and Dawson (personal communication, 1986) suggests a climatic analogue with coastal New Jersey today. Also, it is worth mentioning that beaver-cut sticks have been found in the Beaufort Formation from Ellesmere and Banks islands (Harington, 1978).

To the northeast of our area, about 2 million years ago, at the Tertiary-Quaternary transition, rabbits (Hypolagus sp.) existed in northern Greenland (Kap Kobenhavn) in a mosaic of forest-tundra similar to Labrador (Funder et al., 1985). Also, on the western side of the Canadian Arctic, bones of unusual marine mammals adapted to relatively warm water have been found in latest Pliocene deposits at Ocean Point, northern Alaska (Repenning, 1983).

Quaternary (Pleistocene)

Sparse, scattered finds of Quaternary vertebrates have been made in the Canadian Arctic. Although most of these are remains of Holocene (last 10,000 years) marine mammals from raised beaches, there are a few interesting records of birds and land mammals. The earliest of these reports involve lemming (Dicrostonyx torquatus) and ptarmigan? (?Lagopus sp.) from interglacial deposits (perhaps 700,000 years old) near Jesse Bay on southwestern Banks Island. They suggest a tundra-like environment, but warmer than the present (Miller, 1985). Remains of a small sea bird, the Dovekie (Alle alle), have been found in mid-Wisconsin (about 40,000 years ago) deposits at Cape Storm on southern Ellesmere Island (Blake, 1980). This was the first recorded evidence of an ice-age bird from the High Arctic of Canada. Marine shells from the fossil-bearing deposit indicate a shallow marine environment with subfrigid to cold-temperate conditions in this ice-free enclave.

Mammoth (presumably tundra-adapted woolly mammoths) remains--evidently of late Wisconsin age (about 25,000 to 10,000 years ago)--are known from Cape James Ross on southwestern Melville Island (Kindle, 1924; Blake, 1974; Harington, 1978), northern Banks Island, and other localities along the Beaufort Sea coast of the Northwest Territories and near the Mackenzie Delta. Possibly tundra muskoxen survived the Wisconsin glaciation on a western Banks Island refugium, for remains from Bernard and Masik river areas have been radiocarbon dated at greater than 34,000 B.P. and about 11,000 years B.P. respectively (Maher, 1968; Harington, 1978). Of great interest paleoclimatically is the skull fragment of a saiga antelope (Saiga tatarica) from Baillie Islands. Presumably, it (with mammoth, bison and small horse fossils from that locality) is indicative of steppe-like grassland conditions along the arctic coast of northwestern North America during the last glaciation (Harington, 1981A).

Beginning about 12,000 years ago, the Pleistocene megafauna that occupied refuges in northwestern North America became extinct. It is worth noting that the Bering Strait reopened then and easterly-moving storm tracks shifted northward until their source lay in that region, producing warmer, wetter conditions in northwestern North America. Consequently, large tracts of cool, dry steppe-like grasslands gave way to expanded spruce forests and boggy terrain. More northerly areas, and those at higher elevations, became tundra. Could such striking changes have led to the demise of the large ice age mammals such as large-horned bison (Bison priscus), camels (Camelops hesternus), woolly mammoths (Mammuthus primigenius) and small horses (Equus lambei) that were adapted to drier more open ground? Presumably, these species would have been confined to progressively smaller areas of suitable habitat, until they died out naturally or were exterminated by human hunters (Harington, 1980A).

Quaternary (Holocene)

Following this Pleistocene megafaunal extinction some 10,000 years ago, we are left with the modern Canadian Arctic vertebrate fauna. Remains, particularly those of marine mammals, tend to become more numerous toward the present. However, a few early Holocene (10,000 to 5,000 years ago) sites have produced interesting bones of land mammals and birds. Fielden (Fielden and De Rance, 1878), a member of Nare's Royal Navy expedition to northern Ellesmere Island, collected collared lemming (Dicrostonyx torquatus), caribou (Rangifer tarandus), muskox (Ovibos moschatus) and ringed seal (Phoca hispida) specimens from raised-beach deposits near Alert. Presumably, they are of similar age to finds of a caribou antler (radiocarbon dated at 8,415 ± 135 years B.P.) and a virtually complete Oldsquaw duck (Clangula hyemalis) skeleton (about 7,000 years B.P.) from raised-beach deposits near Clements Markham Inlet west of Alert (Stewart and England (in press); T.G. Stewart, personal communication, 1984). These reports suggest that these animals had been able to migrate into tundra-like areas and coastal waters on the northern margins of the Ellesmere Ice Cap as early as 8,000 years ago, if indeed some did not survive the peak of the Wisconsin glaciation in refuges there. Presumably, Oldsquaw were migrating to and breeding in northern Ellesmere Island some 7,000 years ago. The species, adapted to tundra lakes and ponds near seacoasts in summer, still breeds in the area (Godfrey, 1966). Farther south, in Polar Bear Pass, central Bathurst Island, remains of a tundra muskox dating to about 8,000 years B.P. indicate that the ice sheet covering that area during the last glaciation had withdrawn sufficiently to allow immigration of muskoxen--perhaps from refuges in western Banks Island (Harington, 1980B).

Marine mammal remains are commonly found on raised beaches throughout the Canadian Arctic (Harington, 1975, 1978, 1985). Many radiocarbon-dated specimens indicate that bowhead whales (*Balaena mysticetus*) and walruses (*Odobenus rosmarus*) were able to occupy waters between the central Canadian Arctic Islands closely following deglaciation of the region, implying a rapid melting of sea ice there during the early Holocene. A.S. Dyke (personal communication, 1985), who has accumulated some 30 radiocarbon dates on whale bones from the Somerset Island--Prince of Wales Island area in this region, has evidence showing strong peaks at about 9,000 and 4,000 years B.P., suggesting greater marine mammal activity at those times, possibly implying the existence of more open water and climatic warming then. Certainly, this finding deserves further investigation.

Quaternary (Little Ice Age)

About 1,000 years ago people of the Thule Culture spread rapidly from Alaska across the Canadian Arctic to Greenland. Evidently, this dispersal resulted from a warming climate (possibly analogous to similar periods about 9,000 to 4,000 years B.P. mentioned above) that led to a widespread melting of sea ice in the region, which in turn provided fresh habitat for bowhead whales (McGhee, 1970; Barry et al., 1977; Harington, 1980). The Thule people began abandoning the Queen Elizabeth Islands some 600 years ago because of deteriorating climate, subsequent major expansion of sea ice, and reduction of their main prey species, the bowhead[1]. These people moved to the margins of their former northern range, became more nomadic and shifted the focus of their hunting to ringed seals, caribou and muskoxen.

Quaternary (1800 to present)

A marked warming of marine climate in the waters between Canada and Greenland from about 1917 to 1940 may have resulted from the influence of Labrador Sea Water during a period of strong zonal winds (M.J. Dunbar, personal communication, 1986). This shift brought about remarkable faunal changes (Jensen, 1939, Dunbar, 1955). Atlantic species that appeared, or increased in range, in West Greenland waters included: Atlantic cod (Gadus morhua), haddock (Melanogrammus aeglefinus), brosme (Brosmius brosme), ling (Molva vulgaris), Atlantic halibut (Hippoglossus vulgaris), herring (Clupea harengus), sping dogfish (Squalus acanthias) and rosefish (Sebastes marinus). The pilot whale (Globicephala ventricosa) and many planktonic animals and plants also invaded these waters. Simultaneously, some fishes such as Greenland cod (Gadus ogac) and capelin (Mallotus villosus)--previously common in southern Greenland waters--moved much farther northward. Harp seals (Phoca groenlandica) became more common off northwestern Greenland, probably because their prey, the capelin, had shifted its range. White whales (Delphinapterus leucas), narwhals (Mondon monoceras), and Greenland halibut (Reinhardtius hippoglossoides) moved north also. The shifting marine fauna forced many Greenlanders, who once lived on marine mammals, to turn to coastal fishing. Peak temperatures in eastern Canadian waters occurred about 1950, some 10 years later than in Greenland. A second peak occurred during the late 1950s to 1960 in Greenland and Iceland, but was less marked in the eastern Canadian waters. The average variation in temperature in the North Atlantic--Subarctic region was about 2 to 2.5 degrees Centigrade (Dunbar, 1982). It is critically important to be able to predict such changes in marine environments. What are the main controlling factors?

At this point, having mentioned climatic change near Greenland, it is worth summarizing the results of a concerted study of climatic change and its effect on vertebrates in the vicinity of Greenland. Much of Christian Vibe's (1967) pioneering work is based on interpretation of historical statistics (from seven sources, the main one being the Koloniregnskaberne, beginning in 1793) on marine mammal, land mammal, and sea bird catches. Vibe related changes in size and distribution of vertebrate populations to three main sea-ice stages:

(1) Stagnation (about 1810-1816). East Greenland Ice does not advance far north into Davis Strait where the Canadian Current dominates. Northwestern Greenland is

relatively cold, dry and stable. Marine mammals and sea birds concentrate in central West Greenland. Winter climate is favourable for caribou in central and northern West Greenland. White arctic foxes increase in the southeastern Canadian Arctic and their percentages (relative to the blue phase) increase in West Greenland. Cod occurs off southern West Greenland, but is seldom abundant except for short periods with little drift-ice. Stable winter drift-ice off Northeast Greenland is favourable for caribou and muskox populations, which increase.

(2) Pulsation (about 1860-1910). Arctic Ocean ice drifts into the Atlantic in abundance. The East Greenland Current and the East Greenland Ice advance far north into Davis Strait in summer. Marine mammals and sea birds decrease in central West Greenland and climate becomes relatively unstable and wet. Caribou decrease in West Greenland because of unfavourable, wet winters. White arctic foxes decrease in the eastern Canadian Arctic, while the blue phase increases in central and northern West Greenland. Cod occur briefly with early drift-ice in Davis Strait. Shifting drift-ice and wet winters off Northeast Greenland hampers growth of the muskox population and results in extinction of caribou there. The bowhead whale populations stagnate in the Atlantic region.

(3) Melting (about 1910-1960?). East Greenland Ice decreases in Davis Strait as the warm Irminger Current strengthens, influencing climate and vertebrate populations. Marine mammals and sea birds increase in northern West Greenland and in East Greenland. West Greenland caribou populations, with good summer grazing and winter pastures often covered by snow and ice, stagnate--except for a short dry period from 1910 to 1920. White arctic foxes increase in the eastern Canadian Arctic and Northeast Greenland, while the blue phase increases in West Greenland. The white percentage decreases in central and increases in northern West Greenland. Cod increase in Greenland waters, being particularly abundant along the west coast. The population increases with little or early drift-ice and decreases with late drift-ice in Davis Strait.

(4) Stagnation (about 1960? - ?). Vibe's study is germane to fluctuations in numbers and range of birds and mammals in the eastern Canadian Arctic, and I suggest, if it has not been done already, that similar statistics (probably based mainly on Hudson's Bay Company records) be examined in relation to weather and sea-ice records for the Canadian Arctic. For example, Catchpole and his co-workers (e.g., Catchpole, 1985, personal communication, 1986; Catchpole and Faurer, 1983) are producing an imposing mass of carefully

assessed data on sea-ice conditions in Hudson Bay, Hudson Strait and the Labrador Sea for the period 1751-1870 based mainly on Hudson's Bay Company ships' log books. Of course, Elton (1924, 1934, 1942, 1949) and Chitty (1938) and Chitty and Chitty (1945) have looked at some of the fur trading records, particularly in relation to arctic fox cycles. Perhaps, more attention should be paid to observations in the Canadian Arctic Islands, where weather records of increasing length are accumulating and where we can achieve a more precise idea of sea-ice changes based on satellite images. Indeed, the Greenland situation could be better quantified and Vibe's hypothesis concerning sea-ice stages could be more rigorously tested--the 50-year cycles seem too precise!

In any case, periodic fluctuations in ocean currents, sea-ice conditions and winter wetness are obviously important among the factors controlling population sizes and ranges of arctic vertebrates. Perhaps, we can see their effect more clearly, and can discern other controlling factors, by examining the significance of core areas of range (e.g., arctic oases for land mammals, birds and fishes; and polynyas for marine mammals, fishes and sea birds).

THE PRESENT

Core Areas (arctic oases and polynyas)

Flying over the Canadian Arctic Islands, one is greatly impressed by their vast size--island after island, sounds, straits and ice caps pass below the wing. Great expanses of bare soil and patterned ground reinforce the fact that most of the region is a polar desert, broken up by a few "emerald islands" of relatively rich vegetation occupied by herds of muskoxen, the odd band of small Peary caribou and nesting waterfowl. These arctic oases tend to be small and rare[2], but they form critical survival areas of range for much of the region's population of land mammals, breeding birds, and freshwater fishes. Although such oases generally allow more species and greater numbers (at least seasonally) of fishes, birds and mammals to occupy relatively confined areas of the Arctic, they do not necessarily assure survival of species like Peary caribou (Rangifer tarandus pearyi). At times, these small caribou must rely on primitive plant communities--usually on higher, drier ground, so this partial exception should be kept in mind. Poorly-vegetated sites can be of great importance because they may be the only ones where forage is available during periods of heavy snow cover or icing (F.L. Miller, personal communication, 1986).

Likewise, these core areas (polynyas) exist in the sea and are instrumental in the survival of marine mammals such as whales, seals, walruses, sea birds and marine fishes throughout the 8-month winters. Nevertheless, particularly in the High Arctic, even these spots can lose their potency for survival of vertebrates because the region is continually on the razor's edge of deteriorating climate.

Arctic Oases

The 71 widely scattered polar oases in Canada (see for example Nettleship and Smith, 1975) form scarcely two percent of the land area in the High Arctic (north of the Northwest Passage) and about five percent of the tundra south of the Passage (Dyson, 1980). The great influence of local geology and climate in the formation of arctic oases should be mentioned. Tozer and Thorsteinsson (1964) first noted the strong correlation between vegetation and surface materials, and Edlund (1986) further refined their observations. Usually there is minimal soil development in the region and vascular plants root directly in weathered rock. The chemistry of the bedrock therefore exerts a major influence on the vegetation. In addition, climate, probably through variations in summer warmth and length of growing season, influences the diversity, abundance and dominance of plant species and communities. This control crosses various types of bedrock and shows a strong elevations and a weaker latitudinal trend (Edlund, 1983). Moisture supply is particularly important--persistent fresh water drives life processes (Bliss, 1977).

Places such as Polar Bear Pass on central Bathurst Island the relatively lush sedge meadows of north central Banks Island offer shelter, water and nutrient-rich ground in which plants and invertebrates flourish, providing food for birds and mammals. Further, they are important winter survival areas for animals like muskoxen, and summer nurseries for North American migratory birds that fly in to breed and molt. Six of these oases have been recognized as refuges for muskoxen: (1) Bailey Point, Melville Island; (2) Fosheim Peninsula, Ellesmere Island; (3) Mokka Fiord, Axel Heiberg Island; (4) Polar Bear Pass, Bathurst Island; (5) Thomsen River valley, Banks Island; and (6) Truelove Lowland, Devon Island (Thomas et al., 1981).

Despite the relatively high numbers of vertebrates occupying these oases, the variety is small compared to temperate areas. The Arctic has only 15 of the world's 3,200 mammals, 70 of its 8,600 birds and less than 50 of its 23,000 fishes (Dyson, 1980). The low diversity of species dictates that the food chain is relatively simple and vulnerable. Muskoxen, Peary caribou, arctic hares, lemmings and ptarmigan all depend greatly upon one species, arctic willow (Salix arctica), as their main food (Thomas and MacDonald, 1986). Also, the lemming is virtually the "hamburger of the North," acting as the main link between plants and carnivores such as the arctic fox (Alopex lagopus), wolf (Canis lupus), Snowy Owl (Nyctea scandiaca), skuas and other birds of prey. And I know from the observations of climate in relation to vertebrate populations in Polar Bear Pass, that mammal populations can be greatly depleted by unusual snowstorms or melt periods (D. Gill and D.R. Gray, personal communications, 1986). For example, an early snowstorm in 1973 dumped about 8 cm of wet snow that froze tight to the ground preventing normal grazing. Three-quarters of the muskoxen died out or migrated. The next year at Polar Bear Pass, 13 rather than the usual 120 muskoxen were seen. And nearly two-thirds of the caribou died or left. Where observers had seen as many as 100 a day moving through the Pass, a year later the largest group was 14 (Dyson, 1980). Furthermore, this drastic winter die-off was widespread: significant losses of Peary caribou and muskoxen occurred throughout the High Arctic. After the winter of 1973-74, only a tenth of the number of caribou estimated on the islands survived (Miller at al., 1977A).

Yet the system survives because there is usually a reserve to draw on should others collapse due to climatic vagaries, etc. Thus, invisible paths over land and over sea ice that connect core areas are critical to the survival of such an ecological network. To some extent, vertebrates in the Canadian Arctic are required to partake of "a moveable feast." For example, Peary caribou commonly migrate seasonally between the Canadian Arctic Islands, apparently to promote their survival while foraging on poorly-vegetated ranges for most of the year (Miller et al., 1977B; Miller and Gunn, 1978, 1980; Miller and Kiliaan, 1980, 1981).

Polynyas

Polynyas are areas of open water surrounded, or nearly so, by sea ice. They are non-linear in shape and may be caused by currents, tides, winds or upwellings, or combinations of these factors. Ones that occur at about the same time and place each year are of the greatest significance to marine vertebrates. There are two types of recurring polynyas: (1) those that remain open throughout the winter; and (2) those that may be ice-covered through the coldest months of some years. However, in the latter case, open water appears in spring (usually by late March or early April), when the first migratory marine mammals and birds arrive. Recurrent shoreleads are also considered here, being of great biological importance--for example, to ringed seals (Phoca hispida), bearded seals (Erignathus barbatus) and their polar bear (Ursus maritimus) predators. The association between marine mammals and sea birds and these patches of open water, has been noted consistently since the first explorers entered the Canadian Arctic, yet we have much to learn about the significance of polynyas for individual vertebrate species. Nevertheless, the influence of these localized polynyas and shoreleads appears to be profound for the survival of viable populations of marine birds and mammals (Stirling, 1981).

Perhaps, "entrapments" (or savssats--the Greenlandic word for entrapment of whales confined to patches of open water during the fall or winter) indicate how important polynyas and shoreleads can be to marine vertebrates--albeit catastrophically! Brown (1986) reported an entrapment of several hundred narwhals and white whales off the west coast of Greenland, and Porsild (1918) recorded one in Disko Bay during the winter of 1914-15 in which about 1,000 narwhals were killed by Greenlanders, and many more were shot but not retrieved.

The Roes Welcome Sound polynya in northern Hudson Bay is mentioned here to give an example of the variety of vertebrates that may be concentrated in such areas (Stirling et al., 1981). This polynya is an important wintering area for white whales (Delphinapterus leucas), walruses (Odobenus rosmarus), bowheads (Balaena mysticetus) and harp seals (Phoca groenlandica). But, occasionally, some large whales may over-winter here. Polar bears (Ursus maritimus) and bearded seals (Enrignathus barbatus) are permanent residents in the polynya.

Whereas polynyas may be important feeding sites for marine mammals and sea birds during late winter and spring, Thomas and MacDonald (1986) consider that productive coastal zones probably assume that role in the mid-late summer when melt-water runoff becomes significant. McLaren and Renaud (1982) note that large summer concentrations of sea birds and marine mammals are found at the juncture of land, sea and glaciers or river inlets, and Thomas and MacDonald

(1980) hypothesize that infusion of nutrient-laden freshwater increases marine food production at these spots.

Sea-bird colonies are special core areas that are considered here, arbitrarily, under polynyas: certainly production of marine fishes and other life in the polynyas adjacent to the usually towering rocky cliffs are of key importance to survival of the colonies. The cliffs themselves provide living and breeding platforms for multitudes of birds, as well as protection from most land predators. Some colonies, like Prince Leopold Island are up to 300 m. high. Although barren looking for a few months, it is one of the major sea-bird colonies in Canada, and the air becomes alive with birds taking flight, as one passes by.

In certain cases, because of their concentration of birds (eggs) and marine mammals, polynyas have attracted human hunting groups for relatively long periods. Schledermann (1980) suggests that the present polynyas in two areas near Bache Peninsula, Ellesmere Island have existed there for at least 2,000 to 3,000 years on the basis of his study of prehistoric settlements in the vicinity.

SPECULATIONS ON THE FUTURE

Evidently rich, but confined core areas (arctic oases on land, and recurrent polynyas and shoreleads in the sea) have greatly promoted the survival of arctic vertebrates for thousands of years. But what happens to these core areas and vertebrates such as fishes, migratory birds, lemmings, polar bears, caribou and muskoxen should extreme climatic cooling or warming occur? Two scenarios are examined with regard to their effect on vertebrate populations and ranges:[4] (a) a cooling whereby most of the Canadian Arctic Islands are covered by ice, and intervening straits are frozen over; (b) a warming whereby open water exists throughout the Canadian Arctic Islands, with land nearly free of glacial ice, and a northward shift of vegetation zones.

Cooling

Presumably, freshwater fish populations would decrease markedly. Not only would there be fewer lakes due to expansion of ice sheets, but those left around the glacial margins would probably be frozen more deeply and frozen over for long periods, decreasing productivity. Marine fishes, marine mammals, including polar bears, would shift their range farther south (a useful analogue being the case where walrus fossils, probably dating to the last (Wisconsin) glaciation, have been found far south of their present range, e.g., San Francisco Bay; Kittyhawk, North Carolina; Montrouge near Paris; and Tokyo--not to mention Moncton, New Brunswick and Qualicum Beach, Vancouver Island in Canada (Harington, 1984). Also remains of arctic-adapted ringed and bearded seals, white and bowhead whales have been found in Champlain Sea deposits (12,000 to 10,000 years ago) in Ontario and Quebec (Harington, 1981B).

In discussing this scenario, it is well to consider the proposal of perennial, solid sea ice as an important zoogeographic barrier to marine mammals (affecting them to different degrees, depending upon their adaptation to ice--for example, a suggested hierarchy of pinnipeds from high to low ice-adaptation is: ringed seal (Phoca hispida), bearded seal (Erignathus barbatus), walrus (Odobenus rosmarus), harp seal (Phoca groenlandica), hooded seal (Cystophora cristata) and harbour seal (Phoca vitulina) (Harington, 1966). Thus, with the straits between the Canadian Arctic Islands frozen solid, most marine mammals would be forced to the peripheries of their former range--perhaps the ringed and bearded seals would be able to survive in areas where ice was relatively thin. The evident exclusion of bowhead whales (Balaena mysticetus) from the central Arctic Islands due to deterioration of climate and freezing over of the straits in the Little Ice Age is another useful analogue. As far as polar bears (Ursus maritimus) are concerned, during the last glaciation their remains have been found at more southerly latitudes (e.g., Kew, England; Hamburg, Germany; north Jutland, Denmark; and Finnoy, southwestern Norway (Kurten, 1968; Harington, 1970A; Blystad et al., 1983; Aaris-Sorensen and Petersen, 1984)). Therefore, like other marine mammals, they would probably be excluded from much of their present range due to solidity of sea ice in the Arctic Islands, and would shift southward with their main prey, the ringed seal.

Presumably, the land mammals, muskoxen (Ovibos moschatus), caribou (Rangifer tarandus) and lemmings (Dicrostonyx torquatus), would be able to maintain smaller populations on the narrow margins of the more widely glaciated Arctic Islands. The stable, cold winters would promote their survival, as it evidently did during Vibe's sea-ice stagnation stage (1810-1860), when caribou and muskoxen were on the increase in Greenland. Again, as happened during the last glaciation, muskoxen would have the opportunity to spread farther south. For example, fossils of tundra muskoxen are known from Montana to New York (Harington, 1970B). Whereas, solid sea ice between the islands would be a significant barrier to marine mammals, it would promote movement of the land mammals between the islands, as well as between the islands and the mainland. Such movement is often important for survival.

Migratory birds could be stopped "cold"! Available nesting areas would shrink as the ice sheets spread over the Canadian Arctic, and forage would decrease in quality and quantity until scarcely any waterfowl, etc. would bother making long flights over or around the massive ice sheets: probably energy costs would be too high relative to breeding success. Alternate areas for nesting might be uncovered on the newly-exposed continental shelf areas--particularly off the Atlantic coast of Canada (Harington, 1978). Another point: like some arctic mammals (e.g., ringed seals and polar bears), certain species of birds that seasonally occupy the Canadian Arctic are relatively aggressive and adaptable. MacDonald and Parmelee (1962) note that in addition to its normal food, the Ruddy Turnstone (Arenaria interpres) quickly adapts to other food sources, even a wolf carcass! They are also able to flip over dry plates of mud to obtain overwintering insects. This behaviour probably has a high level of survival value and suggests that this and similarly adaptable species would be able to survive the cooling better than others. And, as noted previously, Oldsquaws (Clangula hyemalis) may have been able to breed under extremely cold conditions on the northern margin of the Ellesmere Ice Cap during the early Holocene.

Warming

Freshwater fishes would likely increase in numbers and diversity: there would be more open lakes and rivers with greater light penetration, higher temperatures and nutrient productivity. Likewise, numbers and diversity of marine fishes would increase in the Canadian Arctic. Of the marine mammals, probably harp seals (Phoca groenlandica), harbour seals (Phoca vitulina), walruses (Odobenus rosmarus), white (Delphinapterus leucas) and bowhead whales (Balaena mysticetus) would spread farther north and increase in numbers. An analogue for the bowhead whale increase could be taken from evidence of their distribution through the Canadian Arctic about 1,000 years ago, when people of the Thule Culture flourished there. Possibly ringed seals (Phoca hispida) and bearded seals (Erignathus barbatus) would shift farther northward into the coldest waters, becoming reduced in numbers and range. This might be particularly so, considering the widespread loss of land-fast ice that ringed seals generally use for breeding.

But, it is worth noting that mammals are often characterized by their ability to adapt--as can be seen by the presence of these seals in freshwater in Netilling Lake, Baffin Island and river estuaries along the Ontario coast of Hudson Bay (Mansfield, 1967). Similarly, polar bears (Ursus maritimus), the main predators of the ringed seals, are highly adaptable. This can be seen by their ability to survive as far south as James Bay (where the world's southernmost population has developed "earth dens"[5]), by the productive denning area south of Churchill, Manitoba (far south of their "normal" range), and by their ability to make dens on pack ice. Of 24 dens discovered recently along the northern coast of Alaska, 21 were on pack ice (Stirling et al., 1977; I. Stirling, personal communication, 1986). Whatever happens to climate, short of a catastrophe, probably these animals will survive.

As far as land mammals are concerned, warm and wet winter conditions threaten caribou (Rangifer tarandus) and muskox (Ovibos moschatus) survival, as has been noted previously in the Polar Bear Pass situation during 1973-74. Vibe (1967) supports this contention by reference to catastrophic losses of caribou and muskox under wet, unstable winter conditions. Another problem arising is that open water in the straits between the Canadian Arctic Islands would virtually bring migration--so valuable to the survival of these species--to a halt. It could mean that populations surviving on each island could be extinguished piecemeal, without the opportunity to escape to more favourable range elsewhere. Likewise, lemmings and land-adapted carnivores like arctic foxes and wolves would be largely confined to their islands. Further, open water would act as a barrier to mammals from the mainland, that might otherwise have been able to adapt to the warmer, lusher conditions in the Islands. Lemmings, the staple diet of arctic predators, are particularly vulnerable in springs with rapid thaws which allow their burrows to fill with water. At such critical periods, lemmings are liable to die of exposure or to be picked off by predators (D. Gill, personal communication, 1986). So the warming scenario would not favour lemming survival.

On the other hand, migratory birds would probably expand their nesting range, increase their breeding success due to warmer average temperatures and richer forage. These birds might have fewer problems with predators too--particularly if other important prey species such as caribou, muskoxen and lemming populations were severely reduced. Further, the birds could occupy islands isolated from predators (e.g., arctic foxes) by bodies of open water. Likewise, sea birds would prosper because of an enriched fish fauna and clear exposure of many suitable nesting localities.

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FOOTNOTES

[1] While hunting of bowhead whales figures prominently in the life of the Thule people, it is worth noting the wide range of habitats and resources that they exploited toward the eastern limits of their range (e.g., southern Baffin Island (Jacobs, this volume) and the Bache Peninsula region of Ellesmere Island).

[2] But see Edlund's (1986) description of an unusually vegetation-rich zone that covers a large part of Melville Island, making it the richest area of the central and western Queen Elizabeth Islands, comparable to Fosheim Peninsula on Ellesmere Island.

[3] However, diets vary by season and location in the Arctic. Muskoxen generally rely heavily on sedges, especially _Carex stans_, but also cotton grass (_Eriophorum_ spp.), and thus are commonly tied to wet meadows at low elevations. Peary caribou have more catholic tastes, feeding seasonally on a variety of lichens, mosses, flowers and seed heads (e.g., avens (_Dryas_), poppies (_Papaver_), louswort (_Pedicularis_) and knotweed (_Polygonum_)), usually on drier interior sites at higher elevations (Wilkinson et al., 1976; Miller et al., 1977A, 1982; Parker 1978; Thomas and Edmonds, 1983).

[4] Direct or indirect effects of humans on other vertebrate populations are not considered.

[5] During the summer in Hudson Bay and James Bay, open water lasts longer than in most arctic areas. Therefore, the majority of polar bears in this region spend long periods on land (sometimes in "earth dens") away from seals; yet they maintain a larger mean litter size and reproduce more frequently than any other polar bear population in the world (Stirling and Ramsay, in press).

IMPACT OF ENERGY STRATEGIES ON CLIMATE CHANGE

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Solar radiation brings heat from the sun to the earth's surface, but without the atmosphere most of this heat would be lost and the earth would be an inhospitable 68°F colder than today. The atmosphere, through the action of small amounts of carbon dioxide, ozone and water vapor, traps part of the radiation emitted by the earth that otherwise would flow into the cold of outer space. The capacity of the earth's atmosphere to conserve solar radiation is popularly known as the "greenhouse effect."

The last three decades have brought major advances in understanding the links between the atmosphere and climate. Detailed measurements of atmospheric carbon dioxide show an exponential increase that matches the rate at which carbon is placed in the atmosphere by the burning of fossil fuels. Various models of the atmosphere, which greatly differ in complexity, predict that the carbon released over the past century will generate an increase in average global temperature of about 1°F. Laborious analyses of past temperature measurements show that an average temperature increase of about 1°F has, in fact, occurred. A number of gases whose concentration depend on man's activities--ozone, methane, nitrous oxide and the chlorofluorocarbons--also contribute to the greenhouse effect. Expected future increases of these trace gases will double the warming that is anticipated from carbon dioxide alone. Measurements of ancient air trapped in glaciers indicate that the carbon dioxide concentration of the atmosphere was low during glacial periods and high during interglacial epochs. These findings provide irrefutable evidence of the link between atmospheric composition and global climate. With each scientific advance has come a growing public awareness that future climate change could have adverse effects on society. In the following, I discuss how changes in atmospheric composition and in climate are linked to energy use.

Changes in Atmospheric Composition

Modern observations of atmospheric carbon dioxide began in 1958 with the measurements taken by Charles Keeling[1] at a remote site in Hawaii. Keeling's observations show an exponential growth in carbon dioxide on which a periodic seasonal variation is superimposed. The seasonal variation is a product of the biospheric uptake of carbon dioxide during the growing season and its discharge during winter. Keeling also established and maintained an observational regime at the South Pole. The Antarctic records show a similar exponential growth in carbon dioxide concentration, but because the atmosphere at the South

Pole is well removed from biological activity, there is a greatly diminished seasonal variation. Keeling's observations, which have been duplicated in various parts of the world over shorter time intervals, show that during the 1958 to 1987 period, the average carbon dioxide content of the atmosphere grew from 315 to 349 parts per million by volume (ppmv). Measured in terms of metric tons of carbon, 72.4 billion tons (Gt) of carbon have been added to the atmosphere from 1958 to the present.

The difficulty of obtaining air samples uncontaminated by local sources of CO_2 lessens the value of carbon dioxide measurements made prior to 1958. Fortunately, during the transformation of snow into ice in glacial regions, air is trapped in the intergrain spaces of the ice. Figure 1 shows the variation of CO_2 concentration over the past 250 years; data prior to 1958 are taken from ice core determinations.[4] The rise in CO_2 concentration from about 290 to 349 ppmv over the last 100 years corresponds to the addition of 126 billion tons of carbon to the atmosphere. Prior to the beginning of the industrial revolution during the early 1800s, the concentration of CO_2 remained approximately constant, with values of 275 to 285 ppmv.

Carbon Dioxide Production from Burning of Fossil Fuels

Keeling[5] and Rotty[6] have estimated historical releases of carbon from data accumulated by the United Nations. The accuracy of data on fossil fuel emissions depends on the reliability of information in three areas: quantities of fuel used, the carbon content of the fuel and the fraction of the fuel that is burned. The reliability of relevant data improved significantly after the oil crisis of 1973 greatly increased the importance of energy management.

Figure 2 illustrates historical variations in the addition of carbon to the atmosphere through the burning of fossil fuels. The last 120 years of fuel combustion can be separated into four major periods, each with a distinct rate of exponential growth (see Table 1). Between the beginning of the data sets for 1860 and 1913, the world's consumption of fossil fuel and the emission of carbon increased at an average exponential rate of 4.31% per year. Coal was the dominant fuel throughout this span of time. The advent of World War I, the world turbulence of the 1920s, the depression of the 1930s and World War II led to a marked slow-down in the rate of growth of energy use to 1.53% per year. During the twenty-three-year period beginning in 1950, oil made a major contribution to the overall energy picture: world energy consumption grew at a 4.52% per year rate of growth. The rapid growth in the use of oil and gas, far exceeded the increase in coal use (see Table 1). The oil price shock of 1973 began what appears to be another extended period

Table 1

Historical Rates of Exponential Growth of Fossil Fuel Use (%/year)

Fuel/Period	1860-1913	1913-1950	1950-1973	1973-1984
All fuels	4.31	1.53	4.52	1.15
Coal	4.21	0.55	1.78	2.36
Oil	-	-	7.25	0.11
Gas	-	-	7.98	2.31

of low rates of growth for fossil energy use. The 1.15% per year growth rate for carbon emissions was lower than the rate which prevailed during the 1913-1950 interval of war and depression. In 1973, the use of coal once again began to grow at a greater rate than that of oil, reversing a fifty year trend.

From 1860 to 1984, fossil fuels released 184 billion tons of carbon; during this same time interval, the atmospheric burden of carbon grew by 113 billion tons. The increase in the carbon dioxide content of the atmosphere corresponds to 61% of the total carbon released. The bulk of the remaining carbon has dissolved in the ocean, but the total carbon budget is dependent on the biosphere,[9] whose exact role is as yet uncertain.

Temperature Changes Associated with Changes in Atmospheric Composition

The increase in carbon dioxide concentration from 290 ppmv 100 years ago to the present value of about 350 ppmv should be reflected in an increase in surface temperature. While instrumental records of temperature exist over this time interval in most land areas, the analysis of past temperature shifts is extremely difficult. The basic problem is that of detecting a slow, long-term trend in a record made noisy by the continuous fluctuations of short-term weather. A further complication is due to past samplings of temperature that are strongly biased toward land areas. Despite these impediments, the analysis of some 63 million observations over land and sea reveals a distinct warming trend over the past century.[10] As indicated in Figure 3, the increase has been irregular, but the global average warming equals about 1°F. The three warmest years have been 1980, 1981 and 1983. Further, five of the nine warmest years occurred after 1978.

Figure 1. Historical variations in atmospheric carbon dioxide concentration

Data from 1958 to the present are from Keeling's observations at Mauna Loa, Hawaii.[2] Data for the 1740 to 1956 period are taken from measurements of air trapped in glacial ice sheets.[3]

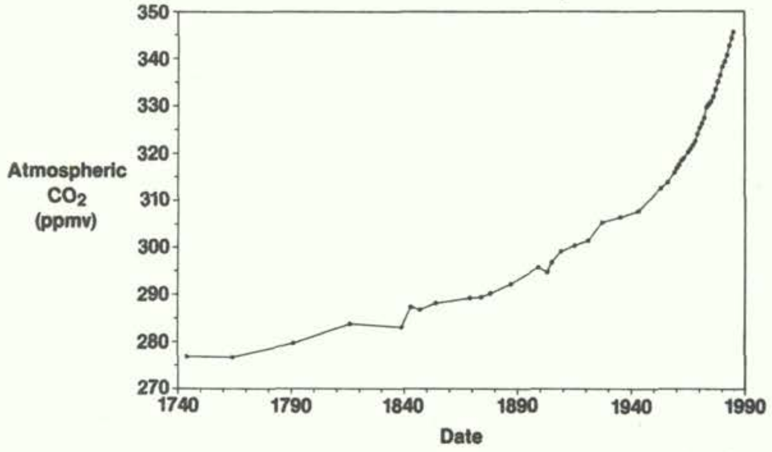


Figure 2. Historical variations in carbon dioxide emission from the burning of fossil fuels (data from Rotty[7] and Keeling[8])

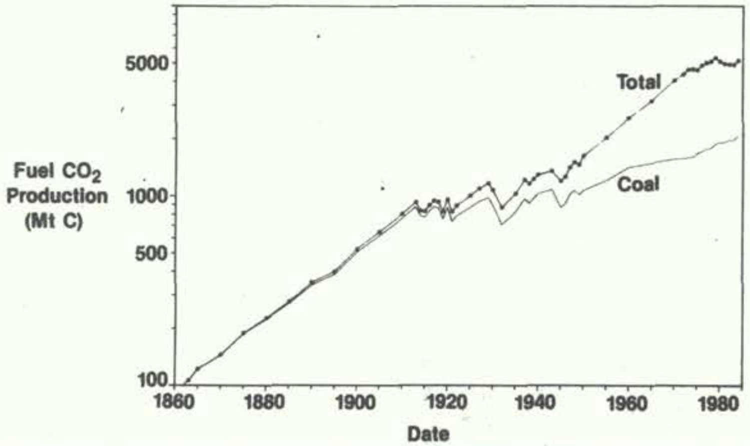
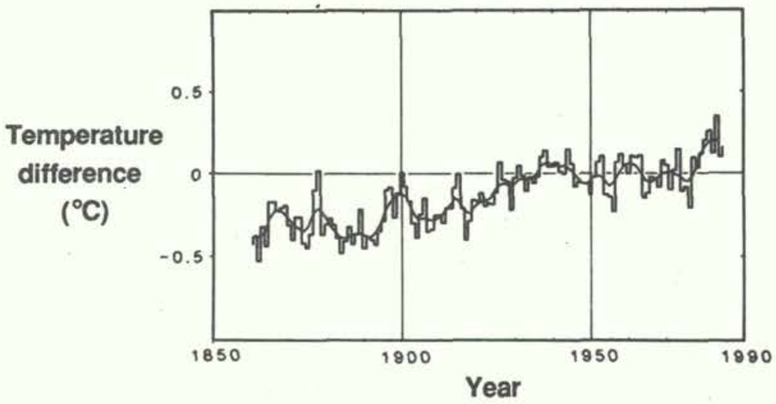


Figure 3. Annual variation of global mean temperature from 1861 to the present (after Jones, Wigley and Wright[11])



Confirmatory evidence of the warming comes from measurements of variations of temperature with depth in permafrost regions of the Arctic.[12] Because of the low thermal diffusivity of rock, temperatures beneath the ground surface represent a systematic running mean of the recent temperature history of the surface; low thermal diffusivity damps out the high frequency variation in air temperature. Permafrost prevents circulating ground waters from perturbing the regime of thermal conductivity. The temperature record contained in the permafrost reveals that surface air temperature has risen 4 to 8°F over the last century. Because the increase at high latitudes is predicted to be 4 to 6 times the global average,[13] the 4 to 8°F Arctic value is in accordance with a global average temperature increase of 1°F.

Trends in Fuel Use

The amount of carbon dioxide generated by fuel use depends not only on the total energy consumed, but also on the mix of fuels. The amount of carbon dioxide generated in delivering a fixed amount of thermal energy depends on the hydrogen-to-carbon ratio of the fuel. Methane, with a high hydrogen-to-carbon ratio, releases less carbon dioxide than does coal in delivering the same amount of thermal energy, as is indicated in Table 2. When "synthetic" fuels are burned, the total amount of carbon dioxide released while generating useful energy is greater than for fossil fuels, because energy is also expended, and CO_2 released, in the initial process of making the synthetic fuel.

Worldwide, the patterns of energy use have changed over the years. As indicated in Figure 2, prior to 1913, the burning of coal provided the bulk of the world's energy and was the principal source of carbon dioxide fuel emissions. By 1950, the percent of energy derived from coal was down to 59%, but coal emissions produced 67% of the CO_2. Between 1950 and 1973, oil became the dominant fuel and carbon dioxide emitter (see Fig. 4). These trends underwent a major shift during the 1970s, as the sharp rise in the price of petroleum prompted a more rapid growth in coal use than in the use of oil (see Table 1). In 1980, coal produced 30% of the world's energy and 40% of the carbon dioxide. By 1984, coal's fraction of energy production had risen to 32%, and coal was responsible for 42% of the CO_2 emissions.

Alterations in fuel mix have produced major shifts in the regional emission of carbon dioxide. In 1950, North America was responsible for 45% of carbon dioxide emissions, the developing world only 6%. By 1984, North America's share had dropped to 25%, with the developing world emitting 15%, as is illustrated in Figure 5.

Table 2

Carbon Dioxide Emissions from Direct Combustion of Various Fuels

Fuel	CO_2 Emission Rate (pounds per million Btu)	Ratio Relative to Methane
Methane	28.2	1
Ethane	32.4	1.15
Propane	34.1	1.21
Butane	35.1	1.24
Gasoline	39.5	1.40
Diesel Oil	41.2	1.46
No. 6 Fuel Oil	41.8	1.48
Bituminous Coal	49.7	1.73
Subbituminous Coal	52.9	1.87

Future Temperature Trends

The estimation of future changes in global temperature that will result from increasing CO_2 levels requires several assumptions: how carbon dioxide emissions are divided among the reservoirs of the atmosphere, oceans and biosphere; estimates of fuel use and fuel mix; and a computational methodology. Given the magnitudes of the required assumptions, any projection is bound to be uncertain. Figure 6 provides an illustrative forecast. The present partition of CO_2 emission among the major reservoirs is assumed to hold into the future. The rate of exponential growth for CO_2 emissions is taken to be 2.3% per year. This rate is double the rate that has held since 1973, but is half that which prevailed during periods of high growth in fossil fuel usage (see Table 1). With these assumptions, the global average temperature change resulting solely from the addition of combustion-generated carbon dioxide will be 3°F in the next 40 years. An increase of this amount is known to equal the temperature change that accompanies the shift from a glacial to interglacial period. If the present rate of fossil fuel use is maintained, the 3°F change in temperature will be postponed for 25 years.

The temperature change illustrated in Figure 6 refers only to changes induced by carbon dioxide. The warming due to other trace gases should also be included in any estimate of future

Figure 4. Variations in the contribution of various fuels to global carbon dioxide emissions

The natural gas curve includes contributions from gas that is flared at the well. The amount of flared gas has decreased with time so that the amount of gas used for energy has increased at a greater rate than the figure indicates. Data are based on Rotty's analysis of United Nation data compilations.[14]

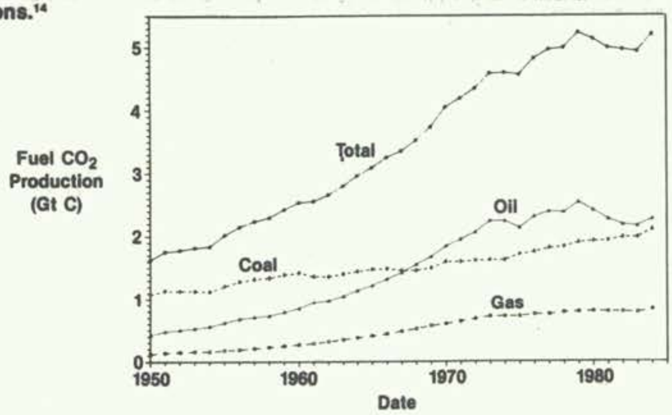


Figure 5. Changes in fractional contribution to global CO_2 emissions by major regions of the world

Eastern Europe refers to the centrally planned economies of eastern Europe, including all of the Soviet Union. C P Asia includes the centrally planned economies of Asia, China, North Korea, Mongolia, North Vietnam, etc. Japan, Australia and New Zealand comprise the Pacific region.

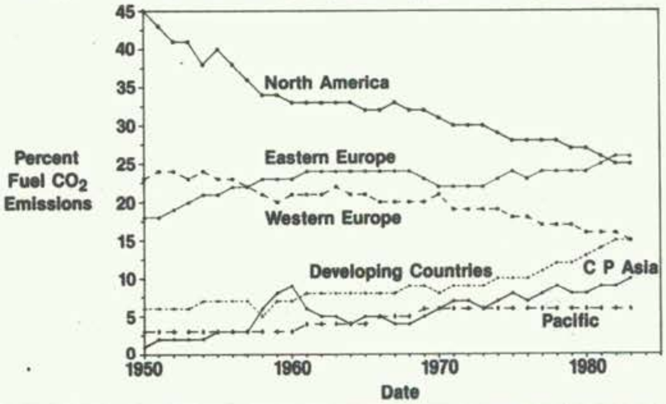
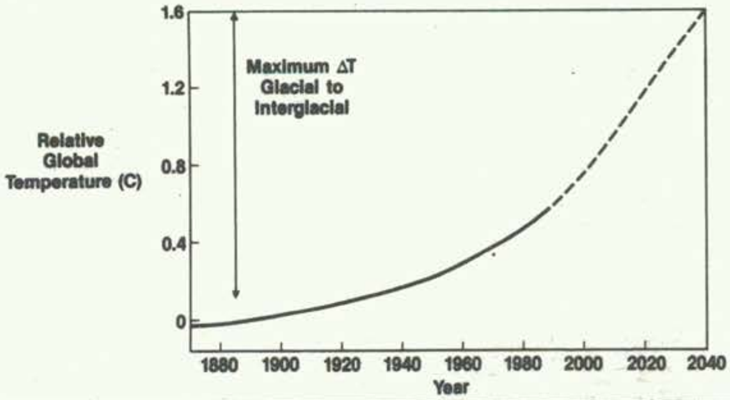


Figure 6. Past and future changes in global mean temperature

Changes are from addition of carbon dioxide to the atmosphere. Other greenhouse gases will lead to further temperature increases in the future.



temperature. Because far fewer data are available on the trace gases, determining their future climatic effects is more uncertain. However, calculations[15] suggest that the total global warming over the next forty years will be about 5 to 7°F, an increase significantly greater than that due to CO_2 alone, and also greater than the increase that accompanied glacial to interglacial transitions.

Conclusions

The burning of fossil fuels changes the composition of the atmosphere. These changes have brought about a warming that is barely perceptible, even when millions of observations are analyzed using sophisticated data reduction techniques. Warming over the next few decades will be significantly greater, and with this warming will come other changes in climate. Attempts to slow climate change must be global in nature; all countries using fossil fuels are contributing to climate alteration. Measures to reduce carbon emissions would include raising energy efficiency and promoting the use of all energy sources that do not contribute to the carbon dioxide burden of the atmosphere, such as nuclear, solar and hydropower. Of the fossil fuels, natural gas releases the least amount of carbon dioxide per unit of energy delivered; coal produces the most. The use of synthetic fuels would hasten climate change since both the production and use of synthetics contribute carbon dioxide to the atmosphere.

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8. Keeling, op. cit., 1973.

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11. Jones, et al., op. cit.

12. A. Lachenbruch and V. Marshall, "Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic," *Science*, **234** (1986), pp. 689-696.

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ENERGY POLICY AND THE GREENHOUSE PROBLEM:
A Challenge to Sustainable Development

Dr. Irving Mintzer[1]

In recent years, industrial and agricultural effluents have increased the concentration of carbon dioxide and other trace gases in the atmosphere. These gases absorb and re-emit low-energy radiation emanating from Earth's surface, thus warming the lower atmosphere. Increasingly, this "greenhouse effect" threatens to alter Earth's climate.

The most important contributors to the greenhouse effect are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3) and the chlorofluorocarbons (CFCs), particularly CFC-11 and CFC-12.[2] Over the course of the last century, the atmospheric concentrations of each of these has increased. During this era, carbon dioxide has contributed the most to global warming. In the last several decades, the annual contribution to warming from carbon dioxide build-up has become approximately equal to the effects of the other trace gases, in part because some of those gases absorb infrared radiation up to 10,000 times more efficiently per molecule than CO_2 does. In the future, the onus for global warming will rest more heavily on gases other than CO_2.[3]

Fossil fuel combustion and other human activities have caused the atmospheric concentration of carbon dioxide to increase by about 25 percent since 1860, ending thousands of years of atmospheric stability. The best recent estimates of the warming commitment that will result from the combined effects of this increase in CO_2 and the concurrent increases in other trace gases suggest a rise of 0.7 to 2.0 degrees C over the average global temperature of the pre-industrial period.[4] Some analysts have

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[1] Senior Associate, Program in Climate, Energy and Pollution, World Resources Institute.

[2] Ramanathan, et al. 1985. "Trace Gas Trends and their Potential Role in Climate Change." Journal of Geophysical Research, 90(D3). 5547-5566.

[3] Hansen, et al. 1986. "The Greenhouse Effect: Projections of Global Climate Change" in J. Titus, ed. Effects of Changes in Stratospheric Ozone and Global Climate Change, 1. U.S. Environmental Protection Agency: Washington, D.C. 199-218.

[4] Ramanathan, et al. 1986. "Climate Change" in Atmospheric Ozone 1985 (Report No. 16). World Meteorological Organization: Geneva, Switzerland.

recently suggested that the eventual warming due to trace gas emissions during the last century may be as high as 1.0 to 2.5 degrees C.[5] A global warming of even 1.5 degrees C over pre-industrial temperatures could alter Earth's climate to an extent outside the range observed in the last 10,000 years.[6] If current emission growth rates continue until 2030, the combined effects of these six greenhouse gases will commit the globe to warm as much as would a <u>doubling</u> of the pre-industrial concentration of carbon dioxide alone (that is, an increase of 1.5 to 4.5 degrees C above the average global temperature of the pre-industrial period).[7]

The historic pattern of greenhouse gas emissions is changing rapidly. The balance of regional CO_2 emissions is shifting, however, toward a greater percentage contribution by the centrally-planned economies and the developing countries. See **Table 1.**

Table 1. Historical Distribution of CO_2 Emissions
(Millions of Tons of C)

	YEAR --->	1960	1970	1980	1985
COUNTRY	United States	783	1149	1249	1186
	Western Europe	523	779	853	780
	Japan	60	195	243	244
	Soviet Union	389	613	871	958
	China	214	211	395	508
	Other Developing Countries	188	336	658	819
	WORLD TOTAL	2440	3724	4859	5102

In 1985, the United States, Western Europe, and Japan contributed almost one-third of global CO_2 emissions from fossil fuels. While the U.S. alone contributed 33 percent of global fossil fuel

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[5] Ramanathan, V. 1987. Testimony to U.S. Senate Committee on Environment and Public Works. January 27.

[6] Hansen, et al. 1986. op. cit.

[7] World Meteorological Organization. 1986. <u>Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts</u>. A conference sponsored by the United Nations Environment Programme, the International Council of Scientific Unions, and the World Meteorological Organization. Report published by the World Climate Programme, World Meteorological Organization: Geneva, Switzerland.

emissions in 1960, its share had fallen to approximately 20 percent by 1985. Over the same period, the Western European contribution declined from 21 percent of the total in 1960 to only 15 percent in 1985. By contrast, the developing country share increased during the last 25 years from 16 percent of the 1960 total to 26 percent of the total in 1985. Although the industrialized countries of the North will contribute more to global emissions in absolute terms than the developing countries of the South, the highest rates of growth in emissions will occur in the rapidly industrializing economies of Asia and Latin America.

At the same time that the regional distribution of emissions is changing, the mix of fossil fuels burned in the production of those emissions is also shifting. See **Table 2.**

Table 2. CO_2 Emissions From Fossil Fuels, 1971-1986
(Millions of Tons of C)

	CO_2 FROM BURNING GAS FUEL	CO_2 FROM BURNING PETROLEUM	CO_2 FROM BURNING COAL	CO_2 FROM FLARING GAS	TOTAL CO_2 EMISSIONS FROM FOSSIL FUELS
1971	553	1946	1594	90	4183
1972	582	2056	1612	95	4345
1973	608	2240	1622	112	4582
1974	616	2245	1620	107	4588
1975	621	2132	1715	96	4564
1976	645	2313	1754	110	4822
1977	646	2390	1812	108	4956
1978	673	2384	1828	106	4991
1979	715	2538	1899	74	5226
1980	721	2411	1922	78	5132
1981	731	2276	1930	58	4995
1982	725	2191	1986	56	4958
1983	733	2170	1992	52	4947
1984	786	2219	2080	52	5137
1985	807	2189	2181	52	5229
1986 (EST.)	825	2283	2209	52	5369

CO_2 emissions form oil combustion have stayed almost constant during the last 15 years, growing at a rate of only 0.2 percent per year. During this period, CO_2 emissions from burning coal and gas have each grown at a rate of approximately 2.4 percent per year. Emissions from the flaring of natural gas have declined at a rate of 3.5 percent per year during this period. Total global emissions of CO_2 have grown at a rate of about 1.2 percent per year over this period.

Emissions of chlorofluorocarbons have grown dramatically during the last 25 years. Emissions of CFC-11 have increased at a rate of approximately 8.0 percent per year, from 40,500 metric tons in 1960 to approximately 280,800 metric tons in 1985. During the same period, emissions of CFC-12 have grown approximately 6.0 percent per year, from 89,100 metric tons in 1960 to 368,000 metric tons in 1985.

Policy choices made today and implemented over the next decade will affect the emissions of CFCs and of CO_2 from fossil fuel combustion. Policies affecting the supply and price of the traditional (and most dangerous) CFCs are being implemented today to minimize the risk of stratospheric ozone depletion. The Montreal Protocol to the Vienna Convention to Protect the Ozone Layer sets important international precedents for environmental protection in limiting the future production of the most dangerous CFCs first to 80 percent and then to 50 percent of their 1986 level.

Choices about energy policy are the best available vehicle for affecting the timing and extent of future CO_2 emissions from fossil fuel combustion. By changing the incentives and subsidies which structure current market decisions about choice of fuels and levels of consumption, energy policy can determine the rate of future emissions growth.

One central question is: "How much can public policy decisions and private investment choices affect warming trends?" To explore this question the World Resources Institute (WRI) developed the **Model of Warming Commitment** (MWC). Combining several existing models of energy use and trace gas emissions with economic growth projections, the MWC projects future emissions of the six most significant greenhouse gases and the resulting increases in temperature.[8]

The MWC tests recent suggestions that policy choices made today can affect the rate and extent of future global warming. This model can investigate impacts on the commitment to future warming of policies which stimulate more efficient energy use, change the global fuel mix, slow tropical deforestation, and limit the production and use of the most dangerous CFCs. The concept of "commitment" points up the fact that the changes brought about by the emission of greenhouse gases into the atmosphere -- from both human and biotic sources -- are essentially irreversible.

An analysis of four scenarios using the MWC illustrates a range of possible global warming outcomes. Each scenario incorporates both broad policy strategies and such narrow

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[8] Mintzer, Irving. 1987. A Matter of Degrees: The Potential for Controlling the Greenhouse Effect. World Resources Institute: Washington, D.C.

Table 3. Energy Policies in the WRI Scenarios

SCENARIO	RELATED ENERGY MODEL PARAMETER VALUE	WARMING COMMITMENT (Centigrade)
Base Case		
• "Business-As-Usual," the inertial model of growth and change in the world energy industry		1980: 0.5° - 1.5° 2000: 0.9° - 2.6° 2030: 1.6° - 4.7° 2075: 2.9° - 8.6°
• No policies to slow carbon dioxide emissions		
• Minimal stimulus to improve end-use efficiency	(Rate of change = 0.8% per year)	
• Modest stimulus for synfuels development	(Final Price = $3.15-$4.25 per GJ in 2005)	
• Minimal stimulus for development of solar energy systems	(Final Price = $16.50 per GJ in 2025)	
• No policy to limit tropical deforestation or to encourage reforestation		
• Minimal environmental costs included in price of energy	($0.30 per GJ for coal; $1.00 per GJ for synfuels)	
High Emissions		
• Accelerated growth in energy use is encouraged		1980: 0.5° - 1.5° 2000: 1.0° - 2.9° 2030: 2.3° - 7.0° 2075: 5.3° - 16.0°
• No policies to slow carbon dioxide emissions		
• No stimulus to improve end-use efficiency	(Rate of change = 0.2% per year)	
• Modest stimulus for increased use of coal	(Rate of Improvement = 0.75% per year)	
• Strong stimulus for synfuels development	(Final Price = $2.75-$3.50 per GJ in 1995)	
• No stimulus for development of solar energy systems	(Final Price = $20.00 per GJ in 2040)	
• Rapid deforestation and conversion of marginal lands to agriculture		
• Token environmental costs included in price of energy	($0.15 per GJ for coal; $0.50 per GJ for synfuels)	
Modest Policies		
• Strong stimulus for improved end-use efficiency	(Rate of change = 1.0% per year)	1980: 0.5° - 1.5° 2000: 0.8° - 2.5° 2030: 1.4° - 4.2° 2075: 2.3° - 7.0°
• Modest stimulus for solar energy	(Final Price = $15.00 per GJ in 2025)	
• Substantial efforts at tropical reforestation and ecosystem protection; more intensive rather than extensive agriculture encouraged		
• Substantial environmental costs imposed on energy prices to discourage solid fuel use and encourage fuel-switching	($0.60 per GJ for coal; $1.50 per GJ for synfuels)	
Slow Build-up		
• Strong emphasis placed on improving energy efficiency	(Rate of improvement = 1.5% per year)	1980: 0.5° - 1.5° 2000: 0.8° - 2.3° 2030: 1.1° - 3.2° 2075: 1.4° - 4.2°
• Rapid introduction of solar energy encouraged	(Final price = $12.00 per GJ in 2000)	
• Major global commitment to reforestation and ecosystem protection		
• High environmental costs imposed on energy prices to discourage solid fuel use and encourage fuel-switching	($1.20 per GJ for coal; $3.00 per GJ for synfuels)	

measures as taxes on particular fuels or limits on certain uses of chlorofluorocarbons. See **Table 3.** Projections from these tests indicate that present-day public policies and private practices could, if continued for several decades, significantly affect the rate and extent of global warming due to the build-up of greenhouse gases. Earlier studies, in contrast, suggested that the state of science severely limits the understanding of policy options.

The Model of Warming Commitment

The MWC simulates the effects of global policies on the build-up of greenhouse gases in three stages. The model projects future production and emissions of the six most important gases, estimates furture concentration by calculating natural rates of gas removal, and evaluates the combined radiative effects of the gas build-up. Numerous assumptions concerning demographics, energy resources and use, and fiscal policies and other economic factors are important to the sub-models used within each stage.

In stage one, the model estimates the releases of carbon dioxide and nitrous oxide during each year of the simulation period. Prompt and banked emissions of CFCs are separated, and increases in methane and tropospheric ozone concentration at exponential and linear rates, respectively, are estimated. In stage two, the processes that remove carbon dioxide, nitrous oxide, and CFCs from the atmosphere are simulated; then the annual growth in concentration of each gas is estimated. In stage three, the warming effects of greater concentrations are estimated using a simple radiative model of the atmosphere. The contributions from each gas are added together. The sum is added to the warming commitment due to emissions over the past 100 years. The model then factors in a range of values that accounts for feedback processes.[9]

To estimate future CO_2 concentrations, the MWC separately accounts for emissions from two sources: fossil fuel combustion (based upon a simulation of the market for commercial energy sources) and emissions from biotic sources. Future concentration of CO_2 is estimated in a simple airborne fraction model that accounts for the effects of the global carbon cycle. An Institute for Energy Analysis (IEA) sub-model is used to project long-term supply and demand for nine primary and four secondary energy forms in each of nine geopolitical regions. This sub-model also provides estimates of regional energy prices. Estimated energy demand is based on data on each region's GNP and population. The sub-model applies constant coefficients in each scenario to express changes in the efficiency of energy use and supply.

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[9] Feedback results as global warming changes atmospheric water vapour content, the extent of sea ice, the average extent and height of cloud cover, and Earth's surface albedo.

The IEA sub-model projects future GNP and fuel prices, describes the future global fuel mix and calculates the amount of fossil fuel combustion releases of CO_2. Estimates of biotic CO_2 emissions related to deforestation and land-use conversion policies are added to the estimated CO_2 released from fossil fuel combustion to produce an estimate of total CO_2 emissions. With an airborne fraction model, annual carbon dioxide emissions are converted to future atmospheric concentrations by introducing the rate at which carbon dioxide departs the atmosphere.

The effects of other greenhouse gases are calculated somewhat differently. The recent growth rate in nitrous oxide concentration correlates closely with the growth in the use of fossil fuels, especially coal and fuel oil. The increase in N_2O emissions in this model follows the rate of growth in coal combustion. Applying a sub-model based on work by Craig and colleagues and modified by Weiss, the MWC computes future N_2O concentration as a function of past concentrations and future emissions.

Chlorofluorocarbons play an important but complex role in both the greenhouse and ozone-depletion problems. Used as aerosol propellants, foam-blowing agents, and solvents, these compounds have no biotic sources but are produced and used solely by industry. In the MWC, an approach developed by the RAND Corporation is used to project future regional production of CFC-11 and CFC-12, two of the most dangerous chlorofluorocarbons. The energy-economic sub-model's population and GNP estimates form the basis for projecting regional CFC demand during three periods of market growth and development. Based on assumptions about alternative variations of the U.S. experience, this sub-model estimates production levels for aerosol and non-aerosol applications of CFC-11 and CFC-12. The MWC then applies an approach developed by ICF, Inc., to convert estimates of future production to projections of future emissions from each of four end-uses; the methodology of Cicerone and Dickenson is then used to convert these estimates of future emissions to projections of CFC concentration.

The contributions of methane and ozone are even harder to gauge than those of chlorofluorocarbons since scientists' understanding of the biological and chemical processes that affect the human and biotic sources of methane and its atmospheric "sinks" is incomplete. The MWC uses an exponential growth function to express future methane emission and removal rates. For tropospheric ozone concentrations, which change in ways that are still poorly understood, it is assumed that the increase will be linear to a maximum level in 2040.[10] These

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[10] The build-up could be greater if the model could account for the interactions of ozone with the other greenhouse gases and with emissions of other gases from fossil fuel combustion.

concentrations vary by time of day, among geographic locations, and with latitude and altitude.

To estimate the eventual warming effect of a greenhouse gas build-up, an approach developed by Ramanathan and colleagues is used; it takes into account the effects of changes in concentration of each gas.

Scenarios of Future Energy Use and CO_2 Emissions

Four scenarios of future economic growth and energy use were investigated by WRI using the MWC. Each of the four takes into account a different mix of technical, economic, and policy factors. Demographic factors, including regional population growth rates and the average annual increase in labour productivity, were held constant in the four scenarios. The average annual increase in the efficiency of energy use and supply, the cost of synthetic oil and gas, the cost of solar energy, and the income elasticity of energy demand are some of the technical and economic factors which are affected by the policy strategies embedded in the four scenarios. Policy factors include environmental cost, calculated as a portion of the consumer price of energy, and consumption taxes on energy uses. For each scenario, the MWC creates a snapshot of data for energy supply and use at twenty-five year intervals, beginning in 1975. Energy use and CO_2 emissions increase in three of the four scenarios. See **Figure 1** and **Figure 2**. All four scenarios support the same levels of regional GNP growth, despite the vastly different energy mixes which they imply.

Figure 1. Primary Energy Supply in the WRI Scenarios
(Exajoules per Year)

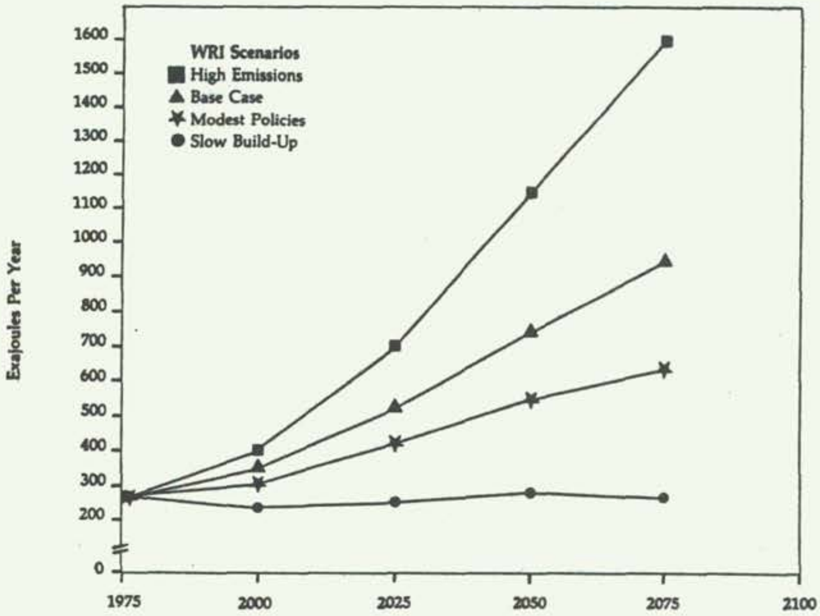
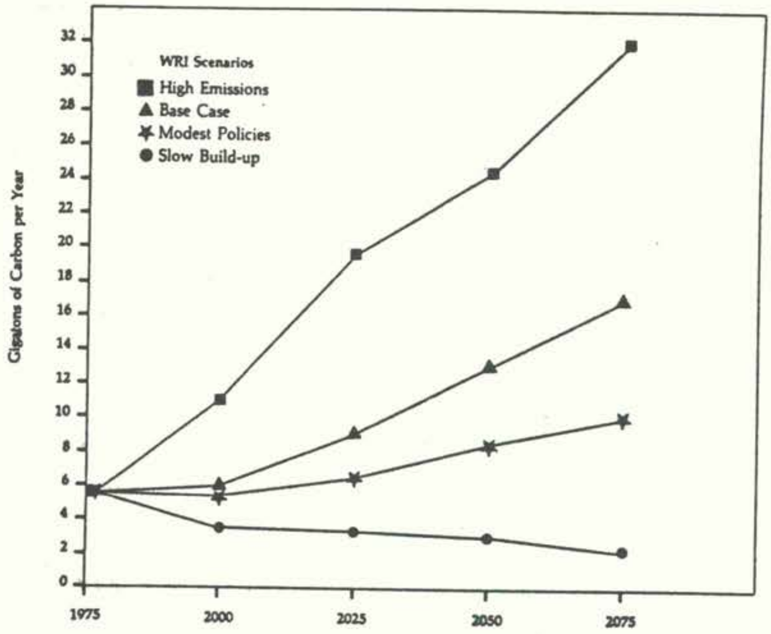


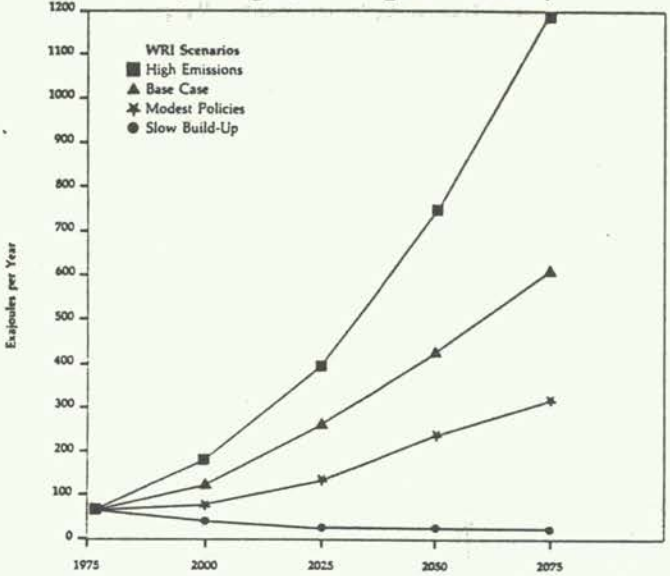
Figure 2. Total Emissions of CO_2 in the WRI Scenarios
(Gigatons of Carbon per Year)



The Base Case projection assumes a "business-as-usual" pattern of growth and change in world energy use. The greenhouse problem is not a major influence on government policies. No efforts are directed toward reducing carbon dioxide releases, governments do little to help improve end-use efficiency or develop solar energy systems, and electricity use increases relative to the use of other energy carriers. Rates of tropical deforestation continue to increase. Total energy use nearly quadruples over the 100-year period, partly because the price of energy includes few environmental costs. Carbon dioxide emissions from commercial fuel use almost quadruple too.

The High Emissions Case reflects aggressive promotion of energy growth with no special attention to the environmental risks of energy use. Although the price of coal doubles over the 100-year span, gas prices increase far more, and coal constitutes 75 percent of the primary energy supply by 2075. Policies encourage the use of synthetic fuel, do not encourage solar energy use, and attach minimal environmental penalties to the use of nuclear power. The increased use of coal and shale leads to an increase in carbon dioxide emission. See **Figure 3**. Generally higher temperatures also result in heightened CO_2 emissions from the biota as the rate of respiration from soil bacteria rises.

Figure 3. Coal Use in the WRI Scenarios
(Exajoules per Year)



Biotic emissions of CO_2 increase dramatically as fuelwood demand rises, and the conversion of forests to agricultural or other development continues unchecked. After fifty years, carbon dioxide emissions have risen seven-fold. At the 100-year mark, tropical forest resources dwindle and biotic emissions of CO_2 decline almost to the base level.

<u>The Modest Policy Case</u> assumes that governments will use a mix of fiscal, tax and other incentives to spur the consumption of less CO_2-intensive fuels and to support the development of more efficient energy technologies. The use of primary energy sources, especially coal, increases more slowly than in the Base Case, but electricity use remains about the same as in that case. Utilities cut their use of solid fuels, so CO_2 emissions decrease from this source. Natural gas and nuclear efficiency grow more rapidly than in the Base Case, as does end-use efficiency. Nations cooperate to reduce the rate of tropical deforestation and to reforest areas where trees once grew. As a result, the net annual biotic release of CO_2 decreases.

<u>The Slow Build-up Case</u> is based on strong global efforts to stabilize the atmosphere's composition by reducing greenhouse gas emissions. Total primary energy use grows very slowly. CO_2 emissions drop by more than half in one hundred years. New policies stimulate higher efficieny of energy use and the introduction of solar energy as its cost drops. Governments cooperate to limit the conversion of forests and begin sustained reforestation efforts. Coal use falls by a factor of four; the biotic contribution of CO_2 in this scenario declines by two orders of magnitude in one hundred years. As in no other scenarios, CO_2

emissions decrease. **The total decrease amounts to over 50 percent.**

Greenhouse Gas Build-up, Climate Change, and Modelling Uncertainty

Concentrations of greenhouse gases in the atmosphere vary by factors of two to five among the four scenarios. The scenarios yield a range of CO_2 concentration, for instance, 420-820 parts per million by volume (ppmv) -- which falls within the lower end of the spectrum of earlier estimates of concentration made by Nordhaus and Yohe[11] and by Edmonds and Reilly.[12] See Figure 4.

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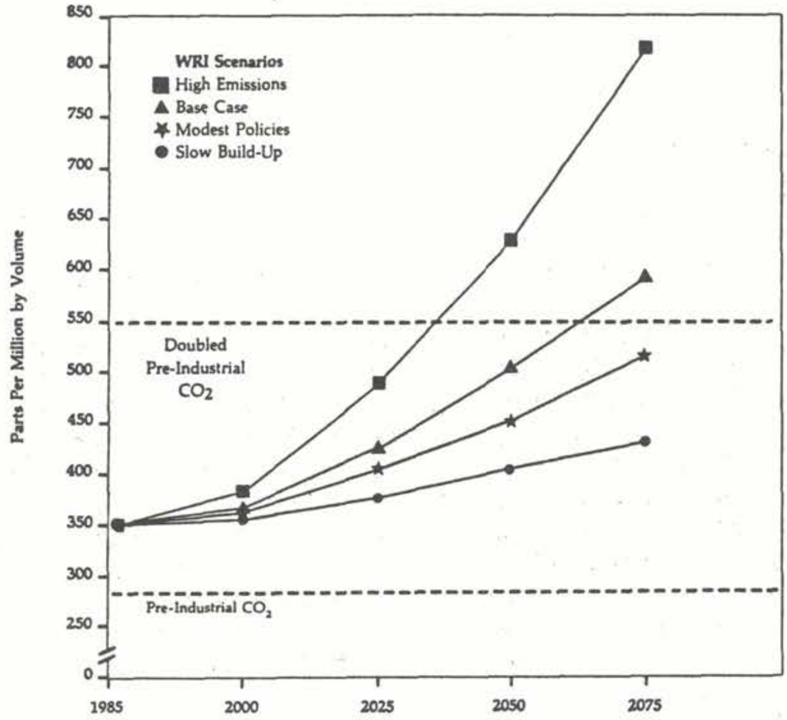
Figure 4. Atmospheric CO_2 Concentration in the WRI Scenarios (Parts per Million by Volume)



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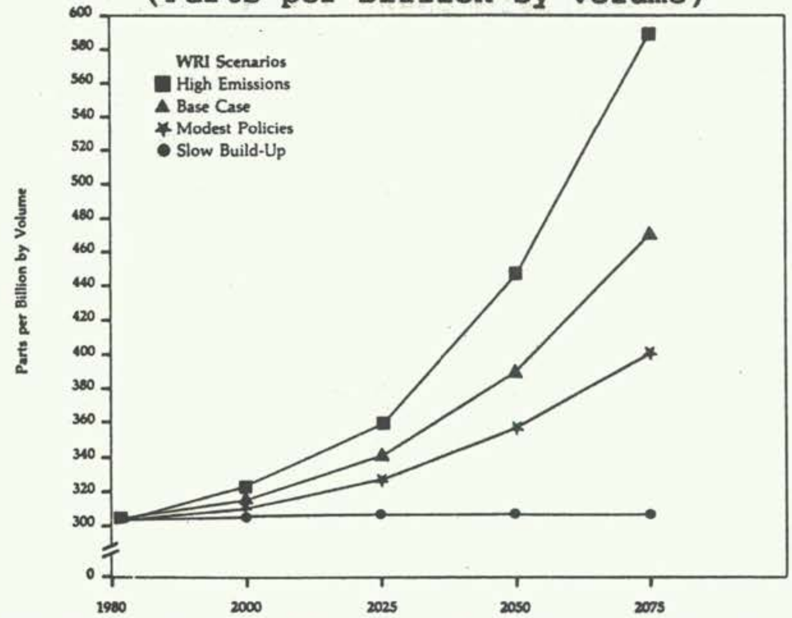
[11] Nordhaus, W. and G. Yohe. 1983. "Future CO_2 Emissions from Fossil Fuels." Changing Climate. National Academy of Sciences: Washington, D.C.

[12] Edmonds, J. and J. reilly. 1984. "Global Energy and Co_2 in the Year 2050." Energy Journal, 4(3). 21-47.

The scenarios show a smaller range, from 445 parts per billion by volume (ppbv) in the High Emissions Case to about 310 ppbv in the Slow Build-up Case, for nitrous oxide concentration. See **Figure 5.**[13]

Figure 5. N_2O Concentration in the WRI Scenarios (Parts per Billion by Volume)



CFC concentration will depend upon how much production and demand increase. In the High Emissions Case, other regions grow at the past rate followed by the United States; in the Base Case, the pace is significantly slower. The Modest Policies and Slow Build-up scenarios simulate the effects of international policies to limit global production and to control key end-uses of CFC-11 and CFC-12. Emissions of the two principal CFCs vary by factors of eight and four, respectively, between the High Emissions and Slow Build-up scenarios. See **Figure 6a** and **Figure 6b**. For CO_2, N_2O and the two CFCs, the range of concentrations projected by the MWC is more conservative than the ranges suggested by earlier studies.

Since so little is known about processes controlling the emissions and removal of atmospheric methane, the model incorporates arbitrary assumptions about growth rates to compute future concentrations of this gas. A factor of three separates the concentrations present in the High Emissions and Slow Build-up scenarios. For perspective, this range is in keeping with

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[13] The rate of growth in coal use, which the model assumes to be the driving force in the rate of N_2O emissions growth, varies by a factor of twenty among the four scenarios.

Figure 6a. CFC-11 Concentration in the WRI Scenarios (Parts per Billion by Volume)

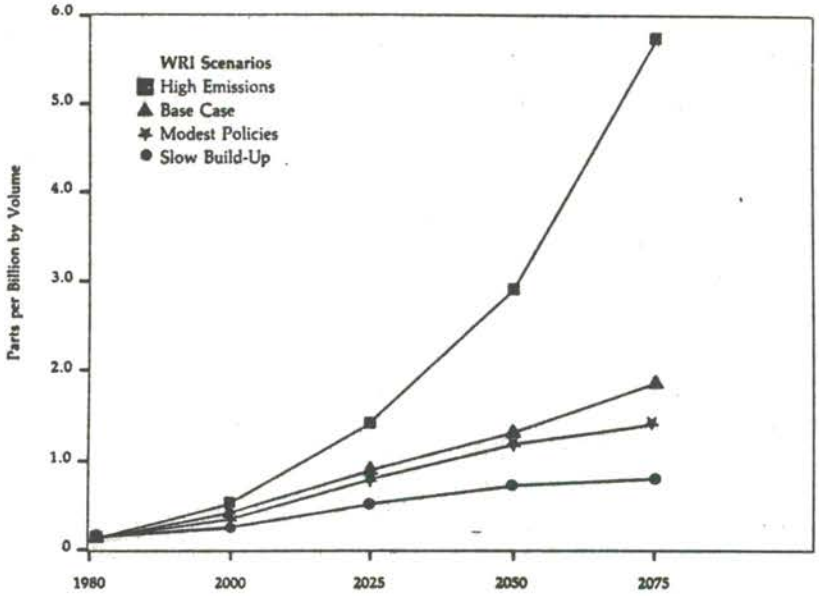
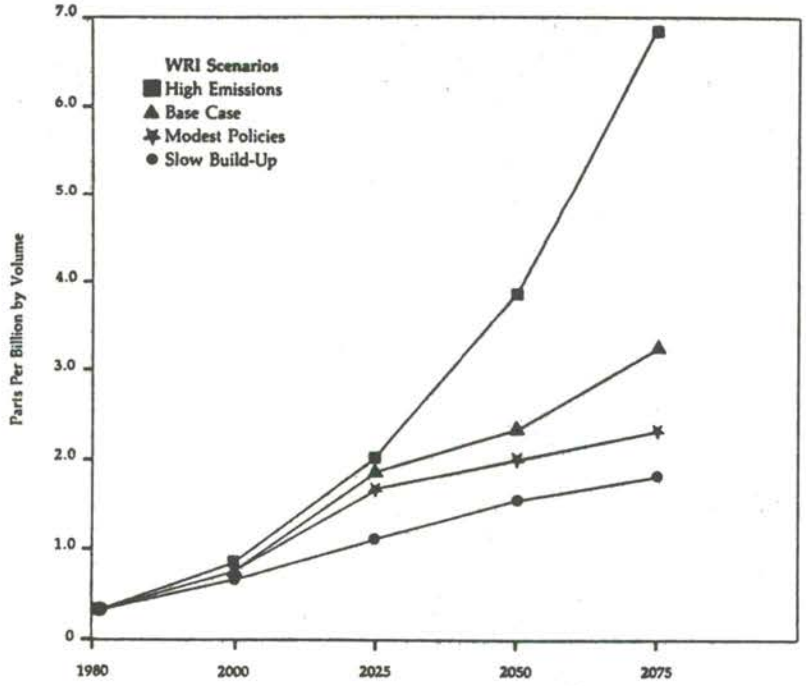


Figure 6b. CFC-12 Concentration in the WRI Scenarios (Parts per Billion by Volume)



earlier studies, and the growth rate for tropospheric ozone compares closely with the rates projected by Ramanathan, et al.[14]

As for the many estimates and assumptions embraced in the Model of Warming Commitment, uncertainties in the data used to project levels of economic activity and emissions of greenhouse gases are significant. Demographic uncertainties and the relationship of such demographic factors as the extent of urbanization to primary energy demand would influence the model could they be quantified. Economic variables, including the rates of increase in regional GNP and GNP per capita, affect projections of the production and emissions of greenhouse gases. Non consensus exists among economists as to how to pin down these rates of change.

New energy technologies may enter markets at unpredictable rates. Structural changes in the western market economies and saturation of certain key end-uses, as shown in recent analyses by Goldemberg, et al.[15], could reduce long-run income elasticities of energy demand. Currently unquantified feedback effects between climate change and future patterns of energy use or greenhouse gas emissions may affect the future warming rate. Also, uncertain are the determinants of the rates of biotic release of CO_2 and the effects of feedback between global warming and future rates of CO_2 uptake by the oceans. For example, additional research and development of coal combustion technology may break the link between coal use and historic rates of N_2O emissions. Finally, documentation of the rate of methane emissions from known sources is lacking.

The models used in this analysis also have structural limitations. The economic sub-model does not disaggregate energy demand well; nor does it represent well the effects of policies to accelerate market penetration, or capital formation, or depreciation as a stimulus for investment. With the sub-model used to estimate future N_2O production, annual emissions may be understated. Moreover, the MWC cannot adequately simulate the effects of either geographic or altitudinal variation in trace gas distribution in the atmosphere because it relies upon a one-dimensional model of the radiative effects.

Modelling Results and Policy Implications

The predictions of warming effects in these four scenarios provide a framework for evaluating the potential for policy to limit future global warming. Two criteria are used to evaluate

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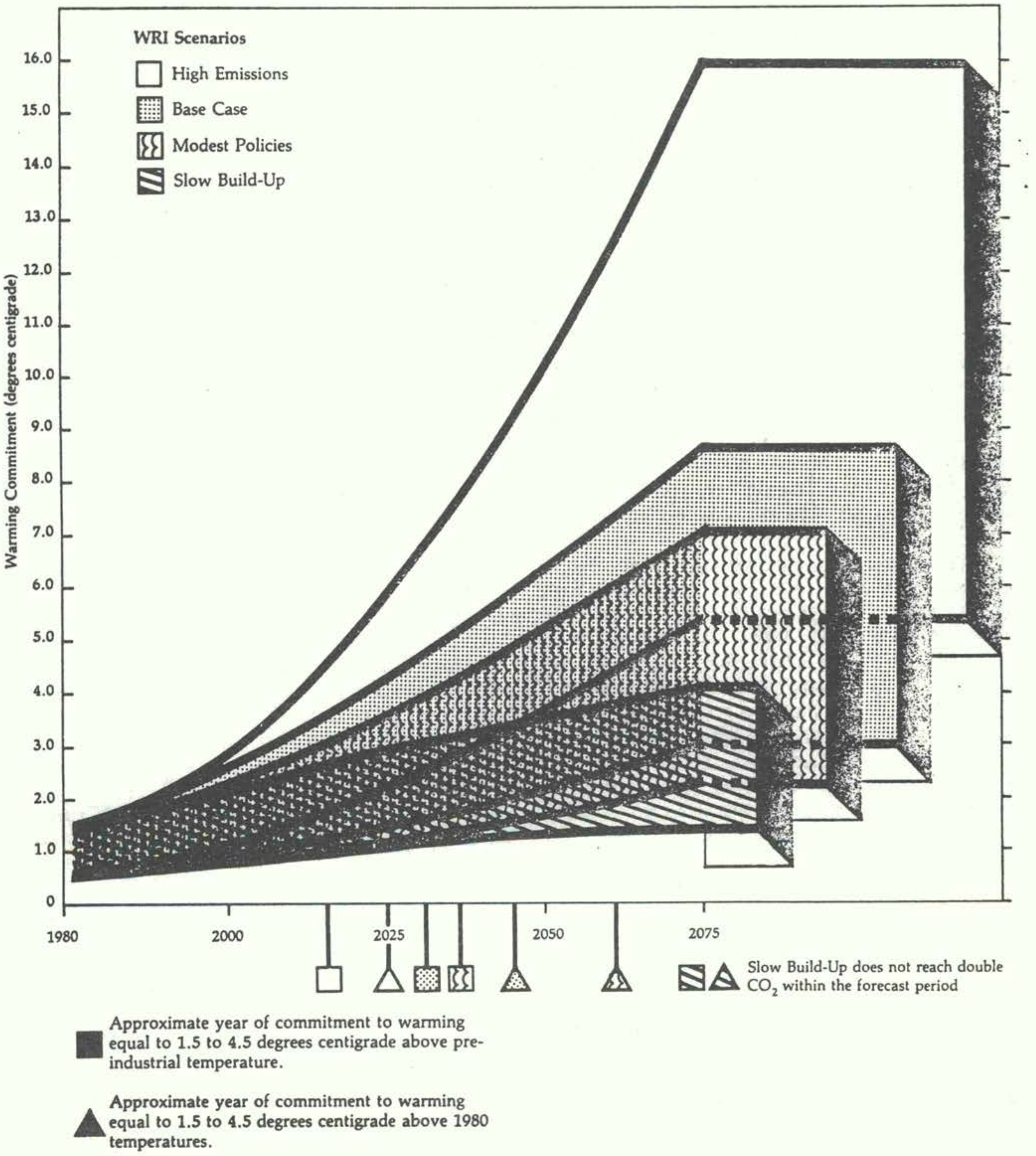
[14] Ramanathan, et al. 1985. "Trace Gas Trends and their Potential Role in Climate Change." Journal of Geophysical Research, 90(D3). 5547-5566.

[15] Goldemberg, J., et al. 1987. Energy for a Sustainable World. World Resources Institute: Washington, D.C.

Figure 7. Commitment to Future Warming in the WRI Scenarios



the scenarios. The first is the date at which the atmosphere is committed to a warming equal to the effect of doubling the pre-industrial concentration of CO_2 alone, i.e., 1.5 to 4.5 degrees C. The second criteria is the total warming commitment in 2075, at the end of the simulation period.

The year when emissions will irreversibly commit us to a warming of 1.5 to 4.5 degreees C above the pre-industrial temperature varies by approximately 60 years, depending upon which policies are adopted. The Slow Build-up scenario brings the planet to that point sometime after 2075; the Base Case scenario by approximately 2030; and the High Emissions scenario by 2015. By 2075, the range of warming commitment varies widely -- from 1.4 to 4.2 degrees C under the Slow Build-up scenario to 5.3 to 16.0 degrees C under the High Emissions scenario. See **Figure 7.**

Without new policies, i.e., under the Base Case scenario, the commitment to global warming by 2030 falls into the range of 1.6 to 4.7 degrees, slightly more than would result from doubling the pre-industrial concentration of CO_2 alone. Further, an increase in emissions, such as that exemplified in the High Emissions scenario, commits Earth to warm by 1.0 to 3.0 degrees perhaps as early as 2000. Under either scenario, the upper estimate of warming commitment by 2075 would cause a climate change that is more radical than anything experienced in the last million years.

Current policies do not "lock in" the planet to the worst of these hothouse futures, but the opportunity to avoid a substantial greenhouse warming altogether is no longer ours-- even under the Slow Build-up scenario. In addition, any delay in making policy choices carries significant consequences. Delaying action by, say, 30 years to remove scientific uncertainties, identify options, establish international consensus, and implement appropriate policies will commit Earth to a warming 0.25 to 0.8 degrees C higher than that which would occur under a Slow Build-up scenario implemented today. The increase that a 30-year delay would bring equals about 30 to 50 percent of the total warming commitment due to trace gas emissions between 1860 and 1980. Clearly, policy choices made today and implemented soon will substantially affect the magnitude and speed of global warming.

Conclusions

Future climate changes represent an important and inevitable legacy of today's industrial activities. Human choices, especially those made about energy policy, will largely determine the extent of those changes. The longer governments wait to identify, agree upon, and implement preventive policies to slow the rate of emissions growth, the more extreme and stringent those policies must be in order to keep the atmospheric build-up within prudent bounds. Clear goals for controlling greenhouse gas build-up should guide the formation of workable policies.

Reducing the risk of economically disruptive climate changes in the future will require international cooperation in a number of areas closely linked to energy policy. These areas include efforts to improve efficiency of energy use, limit long-term commitments to increased use of solid fuels, reduce the biotic contribution to CO_2 by slowing global deforestation, and control the production and consumption of the most dangerous CFCs. It may also be necessary to impose controls on methane leakage from fossil fuel extraction and transportation activities.

The four MWC scenarios demonstrate that achieving the goal of limiting greenhouse gas emissions does not require sacrificing the prospects for economic growth. Following the policies in the Slow Build-up scenario could give society several additional decades to adapt to the unavoidable aspects of climate change. Policy-makers and analysts interested in global warming face a challenge at this juncture: to go beyond the rough investigations reported here and implement specific national and regional policies that minimize the rates of future greenhouse gas emissions while promoting economic growth.

ENERGY-CO_2-GLOBAL CHANGE

Frederick A. Koomanoff
U. S. Department of Energy

Human energy usage (fossil fuel) is the direct cause of increased atmospheric CO_2 levels. This increase in CO_2 will result in climate change and change in vegetation fertilization and water use. These direct effects then will have consequences on all aspects of society and natural systems, which in turn of course affect human welfare.

The dramatic increase in energy usage since 1950 when the world's energy usage was 2623 millions of metric tons of coal equivalents, with the United States representing 45% of the energy usage; growing to 10590 million metric tons coal equivalents in 1985 with U.S. being 25%. The usage relates to the changing global growth and population. For during this same period the global population increased from 2.5-5 billion. This changing world may be visualized when we consider that the number of college students which represent future technology, commerce and industry the basis for new ideas, new concepts and demands...that world college students numbered 6.3 million in 1950 and has grown to 54 million in just 35 years. Urban areas which represent industry and the demands for electricity grew from 179 areas with populations over 1/2 million to 556 in 1985. There is no doubt that the world will continue to change in the years to come with the demand for energy constantly increasing to fulfill humankinds needs.

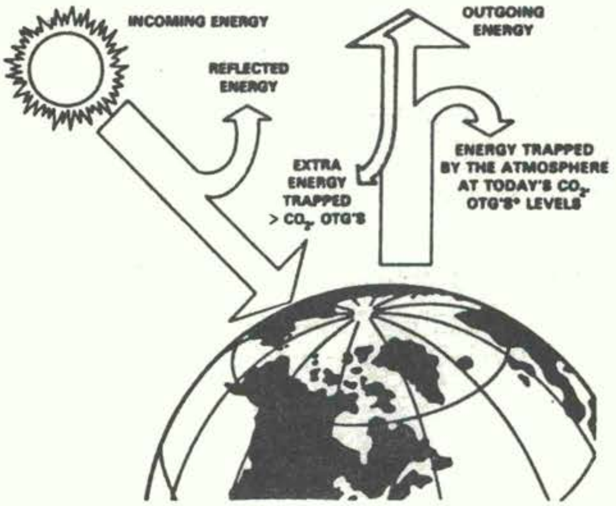
CO_2 is just one of the major greenhouses gases. There are no technological controls, for it is the product of combustion and it represents from 1/2 to 2/3 of the future climate change. CFCs on the other hand are industrial products and technological controls are possible. CFCs with methane and nitrous oxide and the other minor greenhouse gases represent 1/3-1/2 of potential climatic change. The U.S. and Canada represented 45% of all CO_2 emissions in 1950. By 1984 their emissions dropped to 25%. Using China as an example of the developing world, in 1950 China contributions to global CO_2 emissions were 1.4% and in 1984 10%. On a per capita basis, we in North America contribute approximately 5 tons/per person of CO_2 emissions per year with a little more than 1/4 billion population. China on the other hand with a population in excess of 1 billion contribute 0.4 tons per person/year of CO_2.

Although the General Circulation Models (GCMs) represent the combination of excellent intellectual development and of supercomputers, they at present, cannot accurately represent continental or regional climate. On a global basis, their comparison to the observed climate is very good. It can be surmised that on a global basis their estimates for a doubling of CO_2 show the proper sign and magnitude, however, on the continental and regional scales they are not ready to be utilized for estimating climate change.

It is mandatory to compare models to determine why they differ and to increase the resources needed to improve GCMs. It is also mandatory to develop agricultural and ecological systems models where both the effects of increased CO_2 and climate change may be understood.

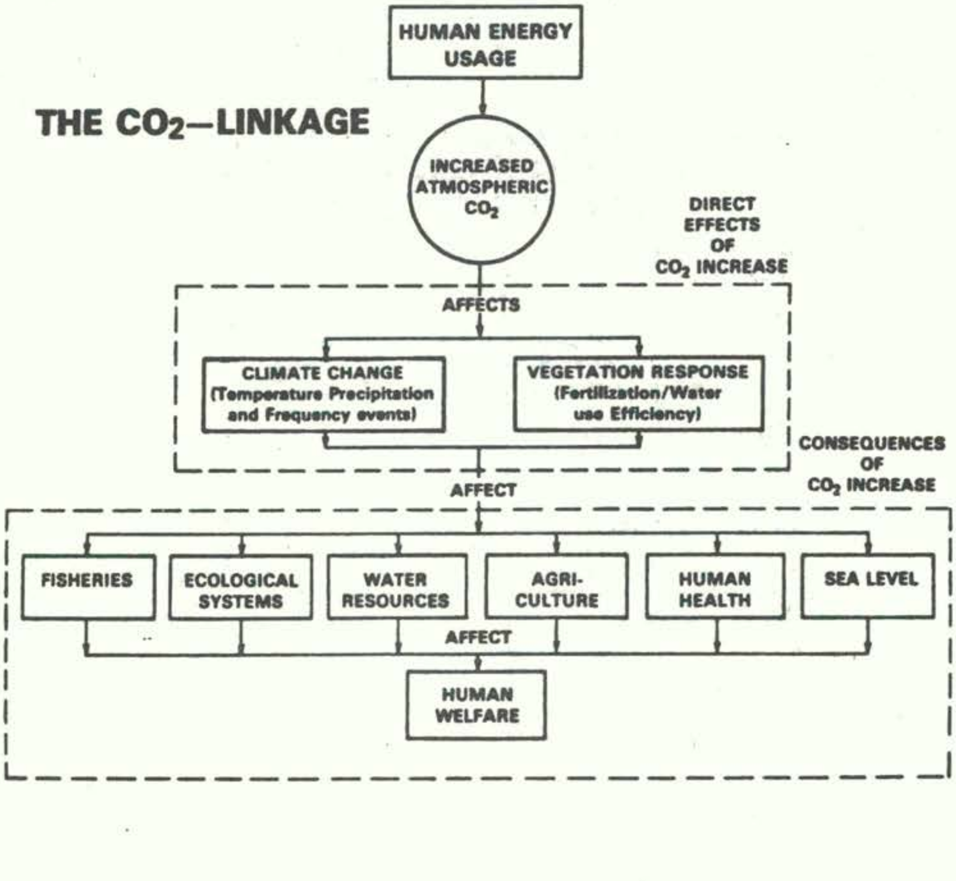
November 1987

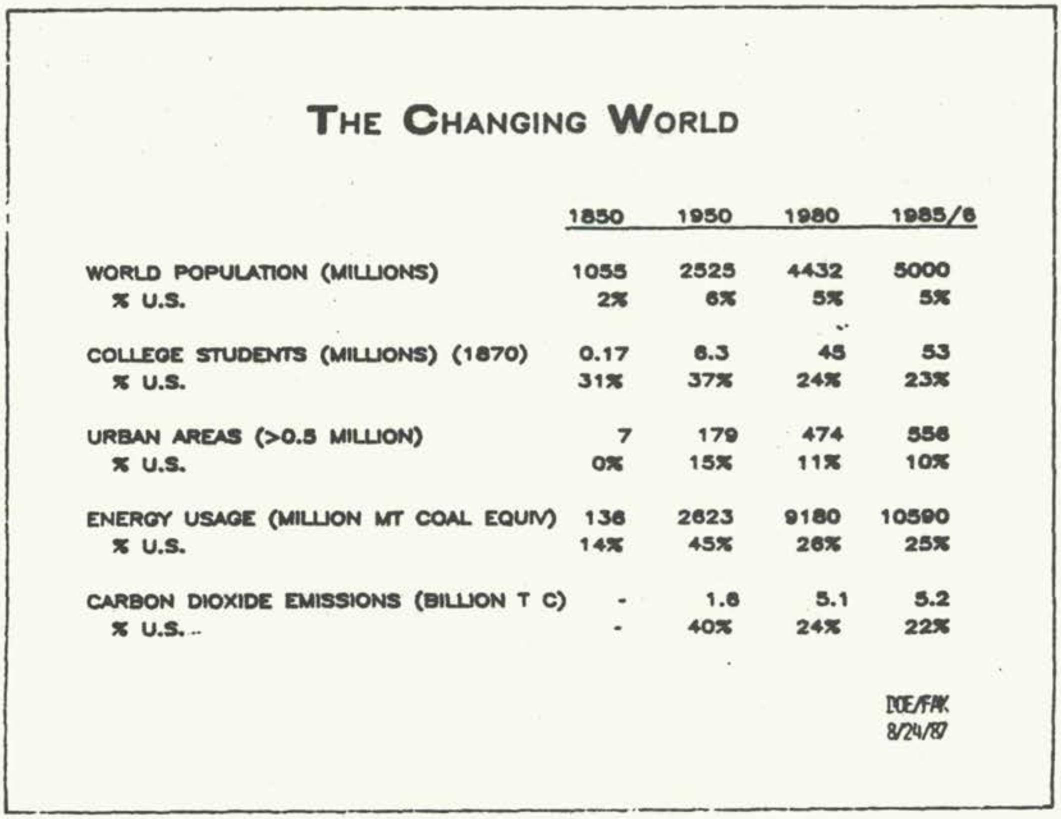
ATMOSPHERIC CO_2 IS ONE OF SEVERAL TRACE GASES THAT ABSORB OUTGOING RADIATION FROM THE EARTH'S SURFACE, THEREBY INCREASING THE AMOUNT OF HEAT RETAINED BY THE ATMOSPHERE AND CREATING WHAT IS REFERRED TO AS THE "GREENHOUSE EFFECT"



*OTG'S = OTHER TRACE GASES E.G., CH_4, O_3, CFC, ETC.

THE CO_2—LINKAGE

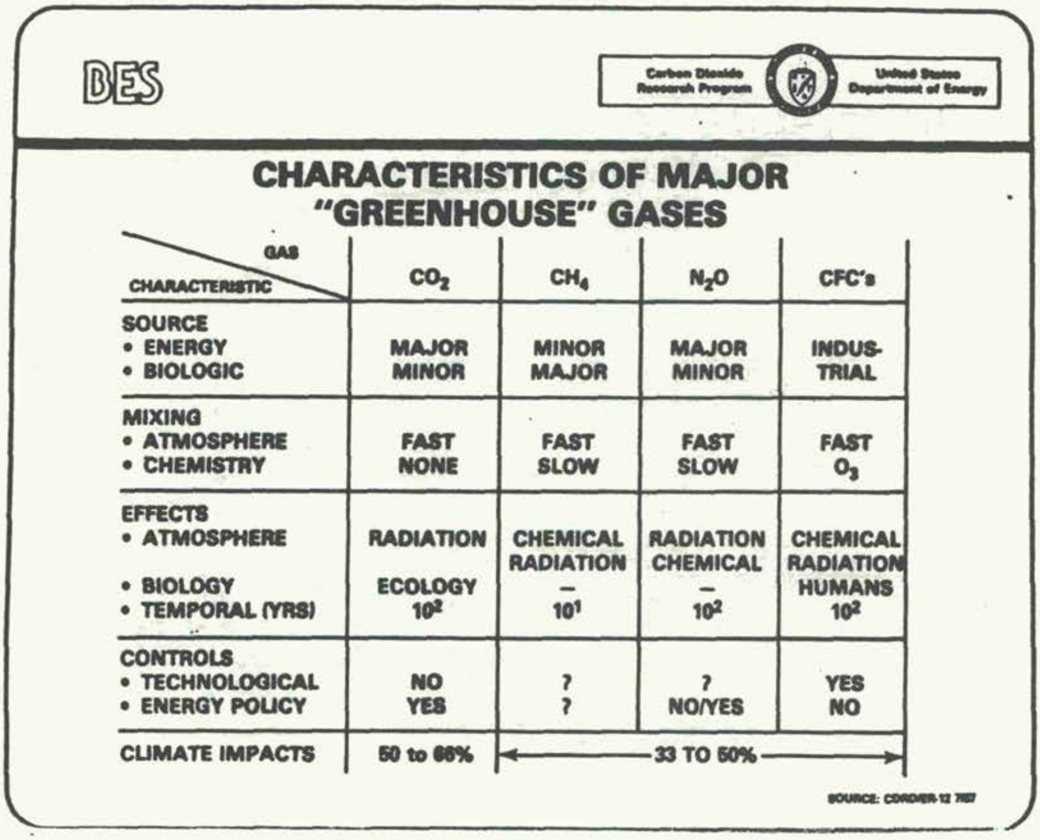




THE CHANGING WORLD

	1850	1950	1980	1985/6
WORLD POPULATION (MILLIONS)	1055	2525	4432	5000
% U.S.	2%	6%	5%	5%
COLLEGE STUDENTS (MILLIONS) (1870)	0.17	6.3	45	53
% U.S.	31%	37%	24%	23%
URBAN AREAS (>0.5 MILLION)	7	179	474	556
% U.S.	0%	15%	11%	10%
ENERGY USAGE (MILLION MT COAL EQUIV)	136	2623	9180	10590
% U.S.	14%	45%	26%	25%
CARBON DIOXIDE EMISSIONS (BILLION T C)	-	1.6	5.1	5.2
% U.S.	-	40%	24%	22%

DOE/FAK
8/24/87



DES

Carbon Dioxide
Research Program

United States
Department of Energy

CHARACTERISTICS OF MAJOR "GREENHOUSE" GASES

GAS / CHARACTERISTIC	CO_2	CH_4	N_2O	CFC's
SOURCE • ENERGY • BIOLOGIC	MAJOR MINOR	MINOR MAJOR	MAJOR MINOR	INDUS-TRIAL
MIXING • ATMOSPHERE • CHEMISTRY	FAST NONE	FAST SLOW	FAST SLOW	FAST O_3
EFFECTS • ATMOSPHERE • BIOLOGY • TEMPORAL (YRS)	RADIATION ECOLOGY 10^2	CHEMICAL RADIATION — 10^1	RADIATION CHEMICAL — 10^2	CHEMICAL RADIATION HUMANS 10^2
CONTROLS • TECHNOLOGICAL • ENERGY POLICY	NO YES	? ?	? NO/YES	YES NO
CLIMATE IMPACTS	50 to 66%	← 33 TO 50% →		

SOURCE: CORD/ER-12 7/87

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Carbon Dioxide Research Program

United States Department of Energy

REGIONAL DISTRIBUTION OF FOSSIL FUEL CO$_2$ EMISSIONS

	1950		1980		1984	
	10^6 TONS C	%	10^6 TONS C	%	10^6 TONS C	%
NORTH AMERICA	724	45	1364	27	1283	25
EASTERN EUROPE (INCLUDES USSR)	291	18	1247	24	1309	26
WESTERN EUROPE	377	23	847	17	784	15
PACIFIC (AUSTRIALIA & JAPAN)	46	3	301	6	317	6
ASIA (MAINLY CHINA)	22	1.4	435	9	521	10
DEVELOPING	94	6	682	13	764	15
TOTAL	1621		5134		5120	

SOURCE: CDIAC/ORNL 7/87

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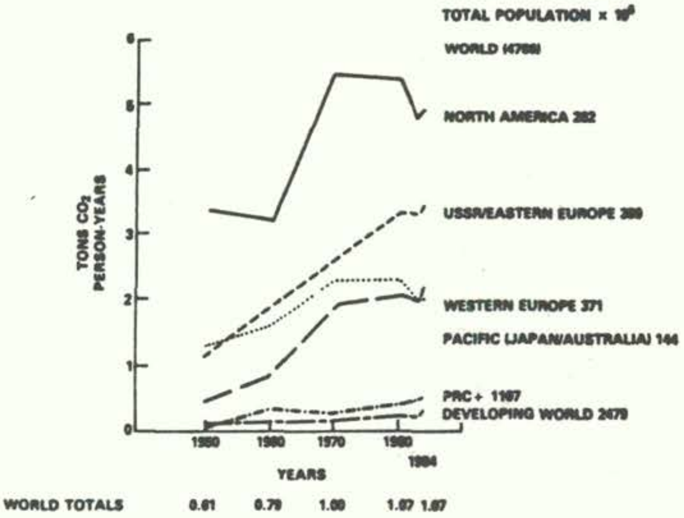
United States Department of Energy

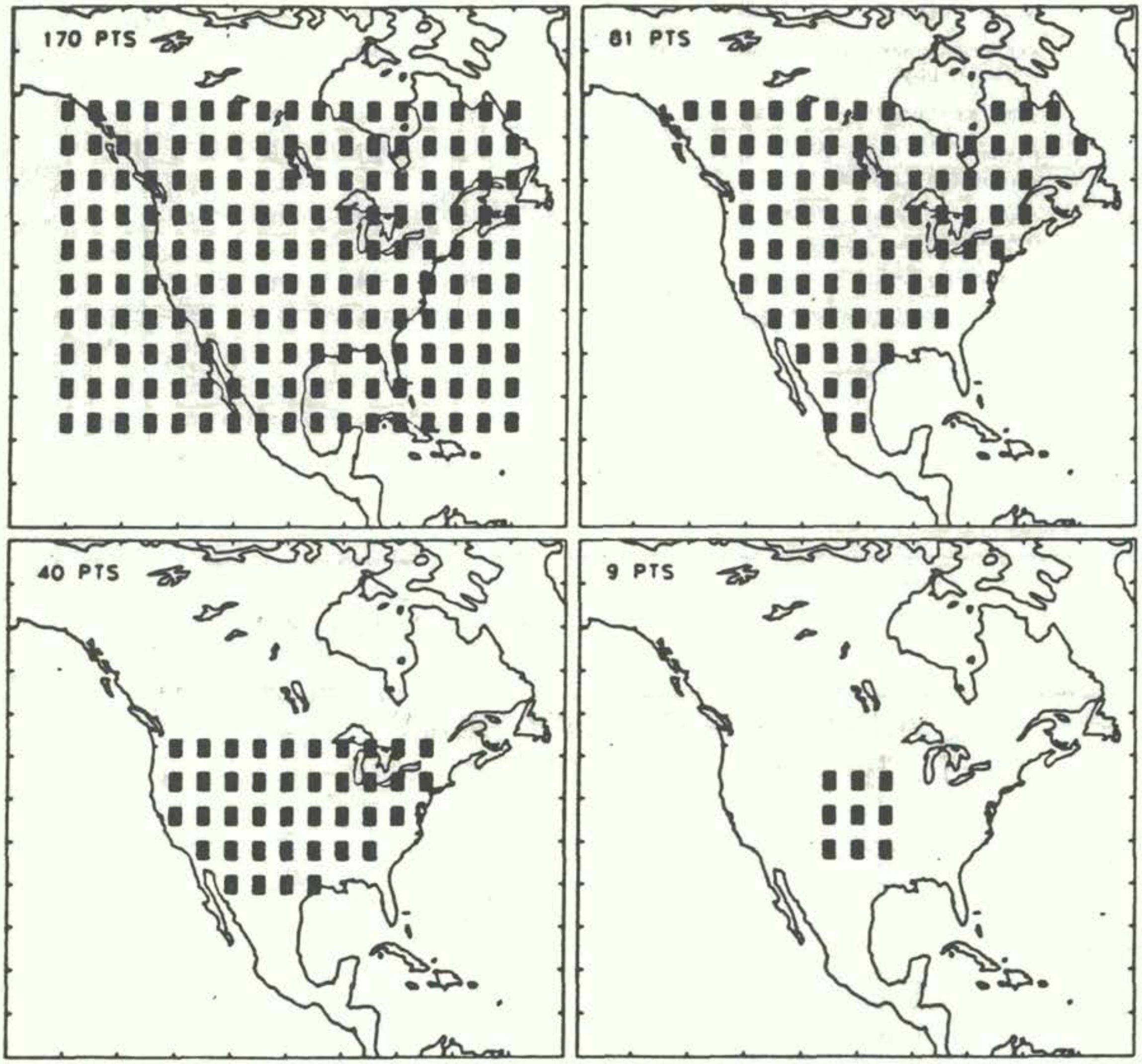
CARBON DIOXIDE EMISSIONS

TONS PER PERSON PER YEAR



SOURCE: CDIAC/ORNL 7/87

FIGURE 1. LOCATIONS OF 4 × 5 DEG. GRID POINTS



$2XCO_2$ TEMP. °C

	SUMMER	WINTER
GISS	+2 TO 4	+4 TO 6
GFDL	+6 TO 8	+4 TO 8
NCAR	+2 TO 4	0 TO 2

$2XCO_2$ PRECIP. IN/MO

	SUMMER	WINTER
GISS	0 TO +1	0
GFDL	0 TO −1	0
NCAR	0	+1

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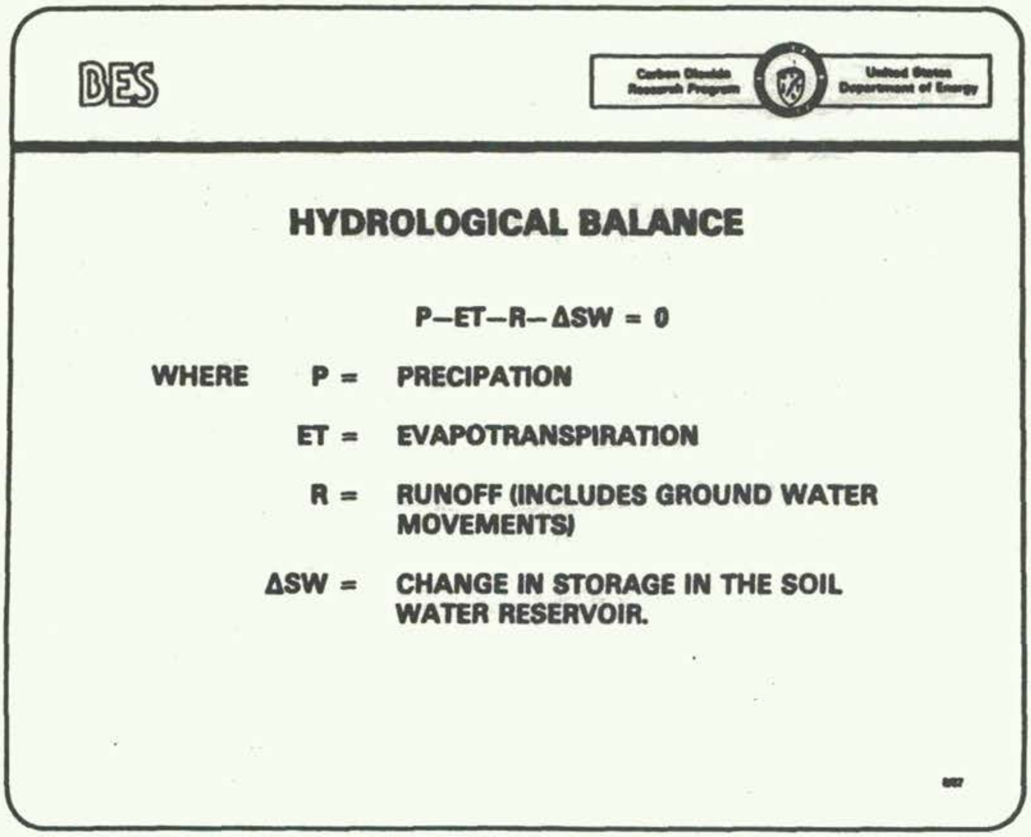
Carbon Dioxide Research Program
United States Department of Energy

Δ°C FROM OBSERVED MEDIAN TEMPERATURE (SUMMER)

SOURCE	GLOBAL	N. AMERICA	CONTIGUOUS U.S.	MIDWESTERN U.S.
OBSERVED $\bar{T}$	13.9°C	18.9°C	23.0°C	23.0°C
CCM	+1.5	+6.0	+6.3	+6.8
GFDL	-0.1	+0.6	+0.1	+3.7
GISS	+0.4	-3.1	-4.5	-4.8
OSU	-0.6	-2.2	-2.2	-1.6



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HYDROLOGICAL BALANCE

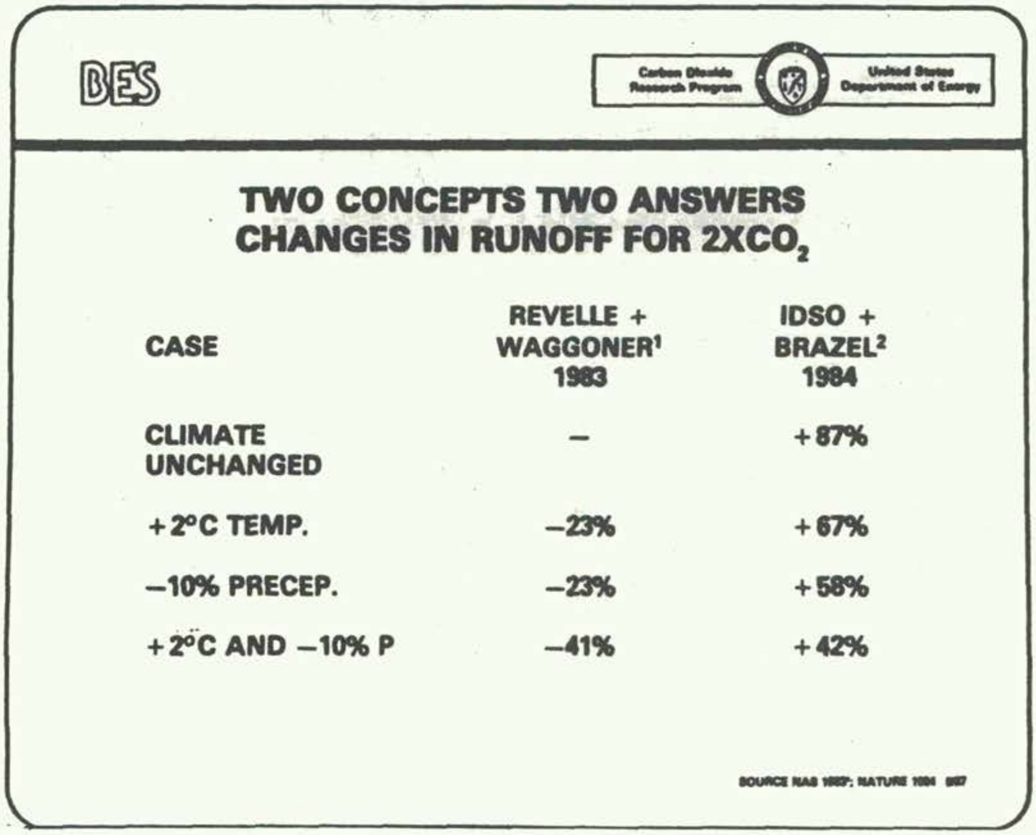
$$P - ET - R - \Delta SW = 0$$

WHERE P = PRECIPATION

ET = EVAPOTRANSPIRATION

R = RUNOFF (INCLUDES GROUND WATER MOVEMENTS)

ΔSW = CHANGE IN STORAGE IN THE SOIL WATER RESERVOIR.



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TWO CONCEPTS TWO ANSWERS CHANGES IN RUNOFF FOR 2XCO$_2$

CASE	REVELLE + WAGGONER[1] 1983	IDSO + BRAZEL[2] 1984
CLIMATE UNCHANGED	–	+87%
+2°C TEMP.	–23%	+67%
–10% PRECEP.	–23%	+58%
+2°C AND –10% P	–41%	+42%

SOURCE NAS 1983; NATURE 1984

Σ

KNOWN

- PAST 25 YEARS GLOBAL ATMOSPHERIC CO_2 INCREASED 316 TO 345 ppm
- MAJOR CAUSE IS MAN'S ENERGY ACTIVITIES
- SCIENTIFIC CONSENSUS — GLOBAL CLIMATE CHANGE DUE TO CO_2 INCREASE AND OTHER TRACE GASES HAS NO HISTORICAL ANALOGUE

UNKNOWN/UNCERTAIN

- TIMING/MAGNITUDE/REGIONALITY OF CLIMATE CHANGE
- MAGNITUDE/RATE OF FOSSIL FUEL USE
- ACCEPTABLE CO_2 LEVEL
- MODIFICATION/ADAPTATION STRATEGIES
- EFFECTS
- OPTIONS (NATIONAL/INTERNATIONAL)

STRATOSPHERIC PROTECTION IN THE WAKE OF THE MONTREAL DIPLOMATIC CONFERENCE

Remarks of

J. Craig Potter
Assistant Administrator for Air and Radiation
U.S. Environmental Protection Agency

Before the First North American Conference on Preparing for Climate Change: A Cooperative Agreement
Washington, DC
October 28, 1987

This is a momentous occasion. It brings together many distinguished scientists, environmentalists, business leaders and government policy makers. We are charged to discuss the consequences of climate change. More specifically, regarding this panel on ozone depletion, to discuss the ramifications of the recent singular agreement by the nations and peoples of the earth to take joint action, in an attempt to prevent some future harmful environmental change from taking place.

Such action by the community of nations is unprecedented. And as with all such events, I think we look at it with some degree of anticipation, as well as with some degree of trepidation.

Two years ago, international efforts to protect the ozone layer had reached an impasse. A framework convention had been signed in Vienna--but past negotiations had failed to produce a protocol to limit chlorofluorocarbons (CFCs).

The United States was pressing for a worldwide aerosol ban. The European community was arguing for a worldwide limit on CFC production capacity. No compromise seemed possible. Yet, one month ago in Montreal, 24 nations signed a protocol that is more comprehensive than either of these positions.

The Montreal protocol is a truly unique environmental agreement. Nations have not waited until damage has occurred but have agreed to take real actions now that will protect the environment for future generations.

Participation in the protocol is truly international. It was signed by the United States, the European Economic Community, and Japan. These nations account for over two-thirds of current CFC production.

The Soviet Union, which accounts for another ten percent, is expected to sign.

In addition to these producing nations, the protocol was signed by developing nations that do not produce CFCs but would be expected to increase their use--and possibly undertake their production--as their economies develop.

Such participation by developing countries illustrates the unusual practicality of the protocol--successfully balancing environmental, economic, and political concerns. In the case of the developing nations, the protocol allows their current use to increase slightly for up to ten years but brings the countries into the protective framework and constrains their long-term use.

Another example of the protocol's practicality is its approximate ten-year schedule for CFC reductions. This provides sufficient time for development of chemical substitutes and emission reduction technologies, while also providing a strong market incentive for doing so.

Having heard of these unprecedented features of the Montreal protocol--its global scope, its widespread support, and its practicality--you may wonder how it was developed.

I believe that the Montreal protocol demonstrates the utility of the risk assessment and risk management process. In the two years immediately following the signing of the Vienna Convention, the United Nations Environment Programme (UNEP) sponsored a series of international workshops on scientific issues and technical options to reduce CFC emissions. Meanwhile, the World Meteorological Organization, with the assistance of 150 scientists from 11 nations, completed its comprehensive assessment of scientific issues, and our agency completed its environmental risk assessment.

These activities laid the scientific and technical basis for rational discussion of the need for and impacts of measures to protect the stratosphere.

The risk management process came into play with a concurrent series of UNEP-sponsored workshops on strategies to control CFC emissions, followed by the resumption of negotiations in December 1986.

Following less than a year of intensive negotiations, on September 16, 1987, the Montreal protocol was signed. Let me briefly summarize its provisions.

The treaty freezes production of CFC-11, 12, 113, 114, and 115 at 1986 levels in approximately 1989, or six months after the protocol enters into force. On July 1, 1993, production will be reduced to 80 percent of 1986 levels. And on July 1, 1998, production will be reduced to 50 percent of 1986 levels.

The protocol also freezes production of Halons 1211, 1301, and 2402 at 1986 levels, starting three years after entry into force.

Special provisions apply for developing countries. If a country's consumption of CFCs is less than 0.3 kilograms per capita, it is permitted to increase its use up to that level for a period of ten years--and then begin its reduction schedule. To meet these needs, the developed countries can increase their current production by ten percent.

In addition, special provisions allow countries to <u>increase</u> their production, if other countries make equal <u>decreases</u>--and permit the Soviet Union to complete construction of two small CFC facilities called for in its latest five-year plan. While these exemptions mean very little in the way of harm to the environment, they facilitate widespread participation by all nations.

The protocol allows trading among compounds based on their relative potential to deplete ozone. This provides greater flexibility in meeting control requirements. Because of their different emission characteristics, however, CFCs cannot be traded for halons.

Finally, the question has been raised--does the protocol go far enough? Should greater or faster reductions be required given the latest evidence from Antarctica? The protocol calls for periodic scientific reassessments. The first is scheduled for 1990 and will likely focus on these and other scientific developments. Through this established process, we should effectively be able to make these different determinations.

Based on our experience with the process leading to the Montreal protocol, let me leave you with a few thoughts that might be helpful in the context of the climate change issue.

First: Continue your focus on scientific assessment. Push your scientists to produce their best work on both atmospheric issues and effects of climate change on the environment. Make sure that the two groups talk to each other. This is good risk assessment.

Second: Be practical. Focus on the costs and availability of solutions before calling for action. This is good risk management--and also good politics.

As I mentioned at the beginning, the unprecedented nature of the Montreal accord gives us reason for both optimism and concern.

On the one hand, the willingness of so many nations to take action to limit the use of CFCs now, in order to prevent possible harm to humans and the environment later, is significant. No nation gains through another nation's loss with ozone depletion. It is a recognition of the fact that independent and unilateral action would not be fruitful. It is a recognition that we must all live at peace with ourselves--and that we must live at peace with the planet earth.

On the other hand, the disquieting note is rung by the fact that we are taking an equally unprecedented step in placing our fate in the hands of planners and modelers. This is a form of centralized command-and-control decisionmaking and regulation which is antithetical to the historic traditions and free institutions of the United States and most of the Western democracies.

Therefore, let us at least ask, "How good is our science?" When it comes to doomsaying, we have certainly been wrong over and over in the past. The track record is not all that encouraging. History is filled with models, predictions, and scares that turned out to have little to do with reality. And in addition to a history of predicting bad consequences which never materialized, our own Government's most sophisticated models threw out the very evidence of the Antarctic ozone thinning because such an occurrence "couldn't" happen.

We also have to be certain that we have neutral science--that it is not policy-laden science. Is our science value free; is it policy neutral? We are all aware of the unfortunate fact that science has been politicized to an extraordinary degree over the past two decades.

I certainly don't mean to suggest that our science is not neutral--especially so with the issue of stratospheric ozone depletion. I am only cautioning that we must place special concern on continuing to keep our science unbiased, especially since the question of climate change is so encumbered with uncertainties.

These are radical and far-reaching steps that we are taking, basing economic planning and regulation on futures modeling. If we take such steps, we must have a very high degree of probability that they are necessary and that the science is right. We need the best and most current scientific information available. We should not be acting on the basis of speculation as to what might happen in the future. This is not something we can afford to be wrong on, for either the environmental implications or the political implications.

FUTURE INFORMATIONAL NEEDS FOR PROTECTING THE STRATOSPHERE

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ABSTRACT

The Montreal Protocol requires a continuing assessment of the threat of stratospheric ozone depletion and of options to prevent such an event. Current efforts to understand the health and ecological impacts of ozone depletion are grossly inadequate to meet this requirement. To benefit fully from the requirement for continuing assessment will require a major scaling up of research on the effects of ultraviolet radiation (UV-B) on health and the atmosphere.

WHAT THE MONTREAL PROTOCOL ACCOMPLISHES

The protocol contains three important kinds of provisions: control requirements; ongoing scientific and technical review; and a framework for corrective action in the event it is needed. While public attention has focused on control provisions, the assessment and the framework for review and midcourse correction are just as important. Here, all three are briefly reviewed.

1. The control provisions and projected environmental effects

Exhibit 1 shows the control requirements of the Montreal Protocol.

EXHIBIT 1

CONTROL PROVISIONS OF THE MONTREAL PROTOCOL

-- Freeze in 1989 on CFC-11,12,113,114,115
-- 20% reduction in 1993 on CFCs
-- 50% reduction in 1998 on CFCs
-- Freeze in 1993 on Halon-1211,1301,2402

By reducing future use and emissions of CFCs and Halons, the Montreal Protocol will yield significant benefits to human health, welfare and the environment. Exhibit 2 summarizes the projected benefits: reduced potential for ozone depletion and for global climate change; fewer cases and deaths from melanoma and

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non-melanoma skin cancer; fewer cases of cataracts; reduced risks to crops and aquatics; reduced damage to outdoor materials; and improvements in tropospheric air quality.

EXHIBIT 2

SUMMARY OF BENEFITS OF THE MONTREAL PROTOCOL
(projected effects through 2075)

	Without Montreal Protocol	With Montreal Protocol
Ozone Depletion (%)	39.9	1.3
Skin Cancer Cases (including melanoma)	154 million	3.7 million
Skin Cancer Deaths (including melanoma)	3.2 million	66 thousand
Cataract Cases	18 million	610 thousand
Reduction in Essex Soybean Yield (%)	> 7.5	0.4
Loss of anchovy larvae (%)	> 25	0.0
Increase in Tropospheric Ozone (%)	> 30.9	1.1
Cost of UV-B stabilizers ($ bill)	4.69	1.57
Increase in Equilibrium Global Temperature (degrees C)	5.8	4.3
Sea Level Rise (centimeters)	97.8	86.7

ASSUMPTIONS: Based on projected ozone depletion for the no controls case (approximately 2.5 percent annual growth in CFC emissions and historic growth in other trace gases) and implementation of the Montreal Protocol provisions (assuming participation rates of 100% for U.S., 94% for other developed nations, and 65% for developing nations). Assumes that the Antarctic ozone hole has no global implications; i.e. that current one-dimensional models adequately project depletion. Effects were computed based on dose-response models developed for EPA's stratospheric ozone risk assessment (U.S. EPA, 1987a), and are reported in its regulatory impact analysis (U.S. EPA, 1987b).

A second major benefit of the control provisions is that they will spur the development of technologies to replace CFCs. Exhibit 3 shows a variety of these technologies and their potential "time of arrival". These expected improvements will lower the costs of meeting current controls and will significantly reduce the costs of meeting further controls should they prove necessary.

EXHIBIT 3

EXAMPLES OF INNOVATIVE TECHNOLOGIES* TO REDUCE CFC EMISSIONS

FC-134a for automotive air conditioners

Helium refrigeration for lesser developed countries

Aqueous cleaning for electronics

* Control options are not inclusive, and were selected from the U.S. EPA's regulatory impact analysis (U.S. EPA, 1987b).

2. Ongoing Assessment

The Montreal Protocol calls for an ongoing assessment of atmospheric science, effects, technical options to limit emissions of ozone depleting substances, and the costs of control strategies. The first such review is scheduled for 1990 and reviews are scheduled every four years thereafter. It is envisioned that these reviews will provide an <u>internationally</u> accepted basis for future decisionmaking about the adequacy of current control provisions. This process could assure that future decisionmaking is based on better information about benefits and costs. In addition, it will provide stronger motivation for developing nations to join the protocol since these nations are more concerned about effects other than skin cancer, and current knowledge about these other effects is weak.

3. Framework for Corrective Actions

The protocol provides means to change control provisions so that new information can be responded to in a timely manner. Because the protocol will assure that a factual basis exists for decision-making and that a structure for making additional control decisions pre-exists, it will not be necessary to take five years to develop a new protocol in the event that additional controls are needed. Should an emergency arise, the world should be ready to respond.

MAJOR UNCERTAINTIES

There are two major uncertainties that currently exist; (1) the global implications of Antarctic ozone hole and of the current monitoring trends of global ozone and (2) implications of increased UV-B on the biosphere and on human health other than skin cancer and cataracts. Decisions about the stringency of control requirements in the Montreal Protocol assumed that not enough was known about Antarctic ozone or global ozone trends to alter control requirements. The decisions made there relied upon the current models that cannot explain these phenomena. While concern was expressed about the impact of UV-B on non-skin cancer effects and on the biosphere, little concrete information was available on these concerns during decisionmaking. Thus, the magnitude of the potential threat of these concerns, which are of the utmost importance to developing nations, remains ambiguously stated.

Antarctic Ozone

Recent information appears to indicate that CFCs are at least contributing to Antarctic depletion, although they do not appear solely responsible. The National Aeronautics and Space Administration (NASA) is chairing a major review of global trends in which some researchers have alleged that depletion is a global phenomenon. The relevance of Antarctic ozone depletion is still uncertain, however. In particular it is not yet possible to state whether the chemical loss mechanisms that are probably occurring in Antarctica could operate in other regions of the earth, possibly at a much lower, albeit harmful, rate. Nor has the potential impact of Antarctic depletion alone, acting as a drain on global ozone abundance, been adequately examined. Finally there has not been an adequate assessment of risks and options to limit the accelerated depletion that would be expected to occur if, in fact, the Antarctic depletion has global significance. Clearly, resolution of these atmospheric issues must have the highest priority.

Immune Suppression

Evidence exists that UV-B suppresses the immune system of animals and humans, although the data supporting the latter hypothesis is much weaker. Almost all work done to date on UV-B induced immune suppression has focused on its role as a co-factor in skin carcinogenesis. Yet solid evidence links UV-B induced immune suppression to the outbreak of herpes simplex and leishmanias, two skin diseases that afflict millions of people throughout the world.

Recently a panel of immunologists, photobiologists, and infectious disease specialists met and concluded that UV-B induced immune suppression has the potential to play a role in many infectious diseases, ranging from malaria to AIDS as well as cancers other than those of the skin. UV-B induced immune suppression may also play a role in the effectiveness of a large number of vaccination programs.

Emphasis must be placed on the term "may". Almost no research has been conducted in these areas (although the little that has been conducted creates cause for concern). Thus at this time it is impossible to state the potential magnitude of this issue in the current environment or in an ozone-depleted world. While there is a tendency to think the problem is not that great (many regions of the world now have very high UV-B levels) it would be a mistake to make that conclusion. Before the germ theory of disease, humours and not bacteria and viruses were blamed for most diseases.

Aquatic Systems

Phytoplankton and zooplankton that form the bottom of the food chain have been shown to have extraordinary sensitivity to UV-B. Theories have been constructed in which the evolutionary pressures that have shaped current aquatic ecosystems have not allowed these organisms to devote energy to their protection from this insult. According to these theories, current levels of UV-B probably plays a key role in the temporal and spatial abundance and lifecycles of various organisms. If true, this would tend to imply that ozone depletion could have an extremely important effect on these ecosystems.

Unfortunately current research has been grossly inadequate to explore this and similar hypotheses. Currently, there is only one or two research projects in the world working on aquatic systems. Critical work on the penetration of UV-B into natural waters, the life cycles of various species, and the population dynamics of aquatic ecosystems has been almost totally ignored. For example, even if aquatic ecosystems near Antarctica begin to appear severely disturbed, the lack of baseline research and fundamental analysis of aquatic systems would delay and probably prevent a clear understanding of what actually is happening there. At this time, the scientific base of knowledge is incapable of projecting a catastrophe before it occurs and may be incapable of assessing the cause of a catastrophe if one does take place.

Crop Impacts

Although there have been field experiments conducted with wheat, soybeans, and corn, current data is so limited that it is impossible to determine the losses in future food productivity for ozone depletion with any degree of assurance. The experiments on corn had severely flawed methodologies, thus invalidating the experimental evidence produced that indicated catastrophic yield reductions. The experiments with wheat were geared to studying its competitive interactions with plants, not yield. They indicate that UV-B can, as theory would predict, have an important effect of competitive balance, but report no yield data. The soybean studies are the longest lasting and best focused. 23 cultivars were screened and two out of three showed sensitivity to enhanced UV-B. A sensitive cultivar (the Essex) showed about a 1 percent loss in yield for a 1 percent ozone depletion in those years in which droughts did not decimate production yields (in the drought years, UV-B seems to have an ambiguous effect). Unfortunately, analysis has not been conducted of the genetic basis of sensitivity of soybean cultivars to enhanced UV-B, on secondary pathways of yield loss (such as competition with weeds, resistance to pathogens, etc.) nor on the potential loss of the gene base if UV-B increases and the implications of that loss if selective breeding and cultivar selection is used to try to reduce yield loss.

In 1988 there is one experiment planned with crops, although limited increases are planned for the future. Nevertheless, current research plans are insufficient to go beyond one or two crops with one researcher for each crop; hardly a sufficient investment to yield progress on this issue. Yet the risk is real-- EPA's Science Advisory Board (SAB), a group of outside scientists that advises the Agency, found that while knowledge was extremely limited, risks to crops represented the greatest global threat of ozone depletion.

Forests

Only the most preliminary work has been done on forests. The results indicate that Lobblolly pine, the most important commercial species in the U.S., may be sensitive to enhanced UV-B. While far too early to draw any conclusions, one researcher has been funded to do a multi-year analysis of this issue. Again, however, even if successful, his experiments will not be independently replicated, nor will the impact of enhanced UV-B on other plantation trees or on natural forests be assessed. Whether enhanced UV-B is a small or major problem will remain a mystery with current research plans for this area.

THE IMBALANCE BETWEEN ATMOSPHERIC RESEARCH AND EFFECTS RESEARCH

In 1987, NASA and the National Oceanic and Atmospheric Administration (NOAA) organized an impressive mission to the Antarctic in an attempt to understand the causes of the springtime depletion in that region. The costs of that expedition were approximately 10 million dollars and it was, in our judgement, worth every penny. It was professionally executed. It included research scientists from dozens of institutions and countries, and it was responsive to pressing needs for better information.

In contrast, between 1977 and 1987, the U.S. EPA spent less than 10 million dollars on all effects research, including all those mentioned earlier in this article, and several other areas including impacts on ground-based pollution levels, polymers, and other concerns. At a recent two-day workshop conducted by EPA to examine plant issues, the majority of the invited scientists had never worked on the issue of UV-B and plants -- too few experienced researchers exist to hold a meeting restricted only to experienced researchers.

The research budget for atmospheric effects probably needs enhancement; in 1987 it probably exceeded 150 million dollars if the costs of satellites are included. The effects budget at EPA was less than 1 million dollars.

A recent committee convened by the SAB to examine research needs for effects research concluded that to make real progress in these areas would require about 17 million dollars a year for the next 6 years. Personally, I am sure that the amount would have been much larger had not each of the scientists known that minimal research funds have been cut in the last five years, (e.g. once there were four crop researchers instead of one or two). Knowledge of past cuts induced a sense of pessimism about stating needs that were any greater than the order of magnitude increase that the panel recommended.

CONCLUSION

The Montreal Protocol calls for continuing assessment. While we all hope for good news from the atmospheric scientists, it would be irresponsible to assume that this will be the case. At the moment we are on a trajectory of research for effects in which future decisions about protecting the ozone layer will have to rely primarily on the atmospheric effects, quantitative estimates of skin cancer, and educated guesses about most other impacts. Considering the important role developing nations will play in protecting global ozone if greater reductions are needed, and the equally important lack of interest which developing nations have shown in skin cancer, one might question whether our current research agenda is adequate to respond to meeting the needs of the Montreal Protocol.

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STRATOSPHERIC OZONE PROJECTIONS
IN LIGHT OF THE MONTREAL PROTOCOL

Presented by

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CHEMICAL MANUFACTURERS ASSOCIATION

To The First North American Conference on
Preparing for Climate Change: A Cooperative Approach
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INTRODUCTION AND SUMMARY

The chlorofluorocarbon-ozone issue is unique among environmental concerns that have resulted in regulations. Unlike regulations which seek to correct existing damage to the environment or to prevent damage that is expected soon, the Montreal protocol is an unprecedented international agreement aimed at averting a problem for the future.

The original concerns were based on computer model results indicating that sustained growth at significant rates in the emissions of fully halogenated CFCs could cause appreciable ozone depletion over the next century and, as a result, undesirable environmental effects. The Montreal protocol addresses this problem by limiting CFC emissions.

In fact, the protocol now provides an extra measure of protection by requiring emissions controls that will limit changes in global ozone amounts to levels that are much smaller than natural variability. Additionally, because uncertainties in the science remain, the protocol requires periodic review of scientific, environmental, technical, and economic information to assess the adequacy of the CFC emission controls.

In the effort to reduce risk to the ozone layer, however, we must avoid overregulation. CFCs serve critical needs in many uses that society considers highly beneficial. Products and materials like modern refrigeration, automotive air conditioning, energy-efficient insulation, critical electronic and medical applications would be impossible today without CFCs. Regulation beyond a scientifically justified safety level will cause unnecessary hardships and potential hazards for society. The review provisions of the protocol ensures continued environmental protection without unduly sacrificing the valuable contributions of CFCs to worker and consumer safety and our standard of living.

In this paper the Fluorocarbon Program Panel (FPP) of the Chemical Manufacturers Association (CMA) presents model calculated ozone changes in light of the Montreal protocol. Results of these calculations show what:

- Calculated changes in global ozone amounts based on a true global freeze at 1986 levels are smaller than natural ozone variations that have been observed over the past 30 years. The first and least stringent control measure of the protocol effectively freezes CFC emissions at 1986 levels.
- Based on the CFC reductions additionally specified in the protocol, global ozone amounts are calculated to be almost constant over the next century.

ATMOSPHERIC MODELS AND UNCERTAINTY

Scientists and policymakers need an accurate method to forecast changes in atmospheric ozone. Forecasts over at least 10 to 20 years are required for policy decisions. Laboratory simulation experiments are inadequate for this purpose because the atmosphere is too large and complex. Thus, the only viable alternative is use of computer models designed to simulate the atmospheric processes that control the concentrations of ozone.

As in all attempts to represent complex natural processes, atmospheric modeling involves the use of approximations as model parameters are not always precisely known. Comparisons with atmospheric measurements indicate that model results can provide reasonably reliable predictions for the next few decades. However, inherent model uncertainties should be kept in mind in making longer term forecasts.

Uncertainties in model results come from several simplifying assumptions and from deficiencies in our understanding of the inputs required for calculations. Major sources of uncertainty are:

- Future concentrations of CFCs and all other trace gases that can affect ozone;
- Simplifications required to simulate the three dimensional motions of the atmosphere;
- Inaccuracies in the physical constants characterizing the photochemical reactions important in controlling the ozone balance; and
- Completeness of the model--whether the model accounts for the major processes responsible for controlling atmospheric ozone.

The Montreal protocol impacts the first source of uncertainty by placing limits on global CFC emissions. This virtually eliminates the high-side uncertainty associated with projections of future concentrations of CFCs.

To evaluate the remaining three sources of uncertainty, scientists test the models by comparing calculated concentrations of atmospheric species with measured values. Overall, these comparisons indicate that models simulate many characteristics of the atmosphere reasonably well. However, there are several important differences between calculated and measured concentrations which limit scientists' confidence in the long range predictive capability of models.

The short term predictive capability is better. A comparison of model calculated and measured concentrations of chlorine monoxide, the key compound in the chlorine catalyzed ozone destruction cycle, tests the reliability of model-calculated effects of chlorine, and hence CFCs (a source of chlorine), on ozone. Chlorine monoxide concentrations determine the rate of ozone destruction by chlorine. Measured concentrations are near, but less than, calculated values throughout most of the stratosphere (see Figure 11-1 on page 606 of WMO Report No. 16). This indicates that models are not significantly underpredicting near-term effects of chlorine on stratospheric ozone. The close agreement indicates that the projections of appreciable ozone depletion associated with large increases in emissions of fully halogenated CFCs should be taken seriously. Thus, precautionary measures to limit growth in CFC emissions are justified. Most importantly, the results of the comparison establish confidence in short-term model forecasts that predict ozone changes associated with constant emission rates of CFCs that are smaller than natural variability.

The recent report of elevated abundances of chlorine monoxide within the "chemically perturbed" region of the Antarctic vortex does not modify the conclusion drawn above.

Preliminary finds reported by scientists participating in the Airborne Antarctic Ozone Experiment indicate that unique meteorology sets up special conditions necessary to maintain the elevated chlorine monoxide concentrations. There is no evidence to suggest that these severe meteorological conditions could ever occur elsewhere. Thus, at this time there is no reason to believe that chlorine monoxide abundances in the chemically perturbed region have any relevance to the rest of the atmosphere. However, should final analysis indicate that further steps are necessary to protect the environment, the review process in the protocol will allow governments to react rapidly.

SCENARIOS OF FUTURE TRACE GAS EMISSIONS AND CONCENTRATIONS

With minor exceptions, limits to future global emissions of fully halogenated CFCs and Halons are well defined by the Montreal protocol. CFC and Halon emission scenarios specified in the protocol (including two different assumptions for CFC emissions in developing countries) are used as the basis for the calculated results presented in this paper. Results of calculations assuming constant emission rates and sustained growth in emissions are also presented for comparison. All emission scenarios used are fully specified in Appendix I.

For the purposes of these calculations, the FPP has adopted the following two emission scenarios for controlled substances in developing countries: (1) an initial emission rate of 10 percent of the global total (excluding emissions under Article 2.6 of the protocol) in 1990 with an annual rate of growth in emissions of 5 percent per year until 1999, when emissions begin to decrease as specified in paragraphs 3 and 4 of Article 2 of the protocol; and (2) identical to (1) except a growth rate of 10 percent. Economics and technology will provide incentives to limit growth in these countries.

Assumptions most commonly used by atmospheric modelers for future concentrations of carbon dioxide, methane and nitrous oxide were used as input for all of the calculations. The assumed future concentrations for these gases are specified in Appendix I.

DESCRIPTION OF MODEL

Model results discussed here were provided by Atmospheric and Environmental Research, Inc. (AER). Results were obtained using a one-dimensional model incorporating the 1987 NASA/Jet Propulsion Laboratory recommended chemical kinetics and photochemical data. Results of the model have been published in many peer-reviewed journal articles and scientific assessment reports (e.g., WMO Report No. 16). The AER model was used by Dr. N.D. Sze during his participation in the model intercomparison held in Wurzburg, Federal Republic of Germany and sponsored by the United Nations Environment Programme. (UNEP/WG.167/Inf. 1.) For a specified scenario of future concentrations of CFCs, methane, carbon dioxide, and nitrous oxide, the various atmospheric models compared in Wurzburg agreed very well in their calculations of globally averaged ozone change. Therefore, the AER model results are representative of one-dimensional model results used during protocol negotiations. In fact, in the Wurzburg model comparison, a scenario similar to Scenario 1 in this paper was used. The AER model calculated approximately one percent greater ozone depletion in 2050 than that calculated by the Lawrence Livermore National Laboratory model (used by EPA in their risk assessment.

RESULTS

Model calculated ozone changes over the period 1940 to 2060 for the four CFC and Halon emission scenarios described earlier are presented in Appendix II. Important features of the calculated ozone changes are described there.

Emissions of CFCs maintained at 1986 levels lead to calculated changes in global ozone amounts that are smaller than natural changes that have been observed over the past 30 years. Results for this emission scenario are shown in Figure 1 along with results from analyses of the 30 year data record of ground-based ozone measurements. The measurements indicate that global ozone amounts have varied (both increases and decreases have been observed) by about 3 percent over periods of about a decade. These variations are believed to be due to natural causes. Model results based on an assumption of constant emissions of CFCs at 1986 rates indicate that depletion would be smaller than 3 percent. Calculated ozone amounts gradually deplete to a value in 2060 only 1.5 percent below the level calculated for an atmosphere containing almost no CFCs (the 1940 atmosphere).

The two calculations based on the Montreal protocol indicate that ozone amounts would remain almost unchanged over the next century. Calculated ozone amounts (results for both these calculations are displayed in Figure 2) first decrease slightly to a value only 0.7 percent below 1940 levels in about 2005 and then increase to a value 0.1 percent smaller than 1940 amounts by 2060. Also, the results are very insensitive to choice of emissions growth rates in developing countries. The maximum difference between calculated ozone amounts for the assumed emissions growth rates of 5 and 10 percent for developing countries is only 0.05 percent.

In order to see the impact of the Montreal protocol, one can compare the above results with calculations based on CFC and Halon emissions allowed to increase at a rate of 2.5 percent per year (i.e., a six-fold increase in 70 years). Model results for the growth scenarios indicate that ozone amounts could decrease appreciably by the middle of the next century. With this assumption, emission rates of CFCs increase rapidly, and lead to rapidly increasing concentrations of chlorine in the stratosphere. These large increases in chlorine concentrations lead to a calculated ozone depletion of 23 percent by 2060 (see Figure 3). This model result, which has been the focus of most discussions of the ozone issue, is now precluded by the international agreement.

CONCLUSIONS

Two major conclusions can be reached from the information presented in this paper.

First, the control measures contained in the protocol ensure an extra measure of environmental protection by requiring emission reductions beyond what current science indicates is required to maintain global ozone amounts within the limits of natural variability. Current scientific information indicates that even the first and least stringent control specified in the protocol--a true global freeze of emissions at 1986 rates--would result in ozone changes that are smaller than natural long term variability throughout the next century. The protocol calls for a two-step reduction of emissions beyond the freeze, resulting in almost no change in calculated ozone amounts.

Second, within the provisions of the protocol, control measures can, if scientifically justified, be modified rapidly to ensure continued protection of the ozone layer. The protocol contains provisions to periodically review scientific, environmental, technical, and economic information to assess the adequacy of control measures. The agreement already takes into account the best information available to protect the environment in the long term, but we know that long range model predictions are uncertain. As new and better information becomes available these predictions will change, and parties to the protocol can respond accordingly in a timely fashion.

APPENDIX I

EMISSION SCENARIOS

Controlled Substances

Estimated global annual emissions for 1986 are 950,000 metric tons for Group I controlled substances (total emissions of CFCs -11, 12, 113, 114, 115), 4,000 metric tons for Halon 1301, and 4,000 metric tons for Halon 1211. The 950,000 metric tons include 150,000 metric tons based on Article 2.6 of the Montreal protocol. The relative mix of emission rates of the controlled substances is held constant over the period 1986 to 2060. Estimated historical emission rates were used for the period 1940 to 1986.

Scenario 1 - True Global Freeze

Total emission rates of controlled substances including Halons are constant over the period 1986 to 2060.

Scenario 2, Case 1 - Emissions Under the Montreal Protocol

Total emission rates of Group I controlled substances grow at a compounded rate of 5 percent per year over the period 1987 through June 1989. On July 1, 1989, the total emissions are split into two groups. During the period July 1989 through July 1993, one group with annual emissions of 870,000 metric tons reduces emissions in 1993 and 1998 in compliance with Articles 2.3 and 2.4 of the protocol. The other group, representing countries operating under Article 5 of the protocol with annual emissions of 80,000 metric tons during July 1989 through June 1990 (10 percent of total emissions exclusive of the 150,000 metric tons based on Article 2.6 of the protocol) increase emissions at 5 percent per year until July 1999, as allowed under Article 5.1 and then decrease emissions in compliance with Articles 5.1, 2.3, and 2.4. Halon emissions are constant over the period 1986 to 2060.

Scenario 2, Case 2 - Emissions Under the Montreal Protocol

Same as Scenario 2, Case 1, except countries operating under Article 5 increase emissions at 10 percent per year over the period June 1990 through July 1999.

Scenario 3 - Growth Scenario (Impossible Under Protocol)

Total emission rates of controlled substances including Halons grow at a compounded rate of 2.5 percent per year over the period 1987 to 2060.

Other Gases - All Scenarios

The scenario for other trace gases' increases are approximately 0.55 percent per year for carbon dioxide, 0.25 percent per year for nitrous oxide, and 0.016 parts per million by volume per year for CH4.

APPENDIX II

FIGURES

Figure 1 - True Global Freeze

The top graph presents relative annual emissions (emissions as a function of time divided by emissions in 1986) for the total of the Group I controlled substances (CFCs -11, 12, 113, 114, 115) and for the Halons over the period 1940 to 2060. Actual 1986 Halon emission rates are less than one percent of 1986 Group I emission rates.

The bottom graph presents the calculated percentage change in total ozone (calculated change in total ozone times 100 divided by calculated total ozone in 1940) for the emissions given in the top graph. Relative changes in global ozone amounts as determined by Angell* (triangles) and Reinsel and Tiao* (pluses) from analyses of ground-based measurements of total ozone are also presented.

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* Personal communication.

Figure 1

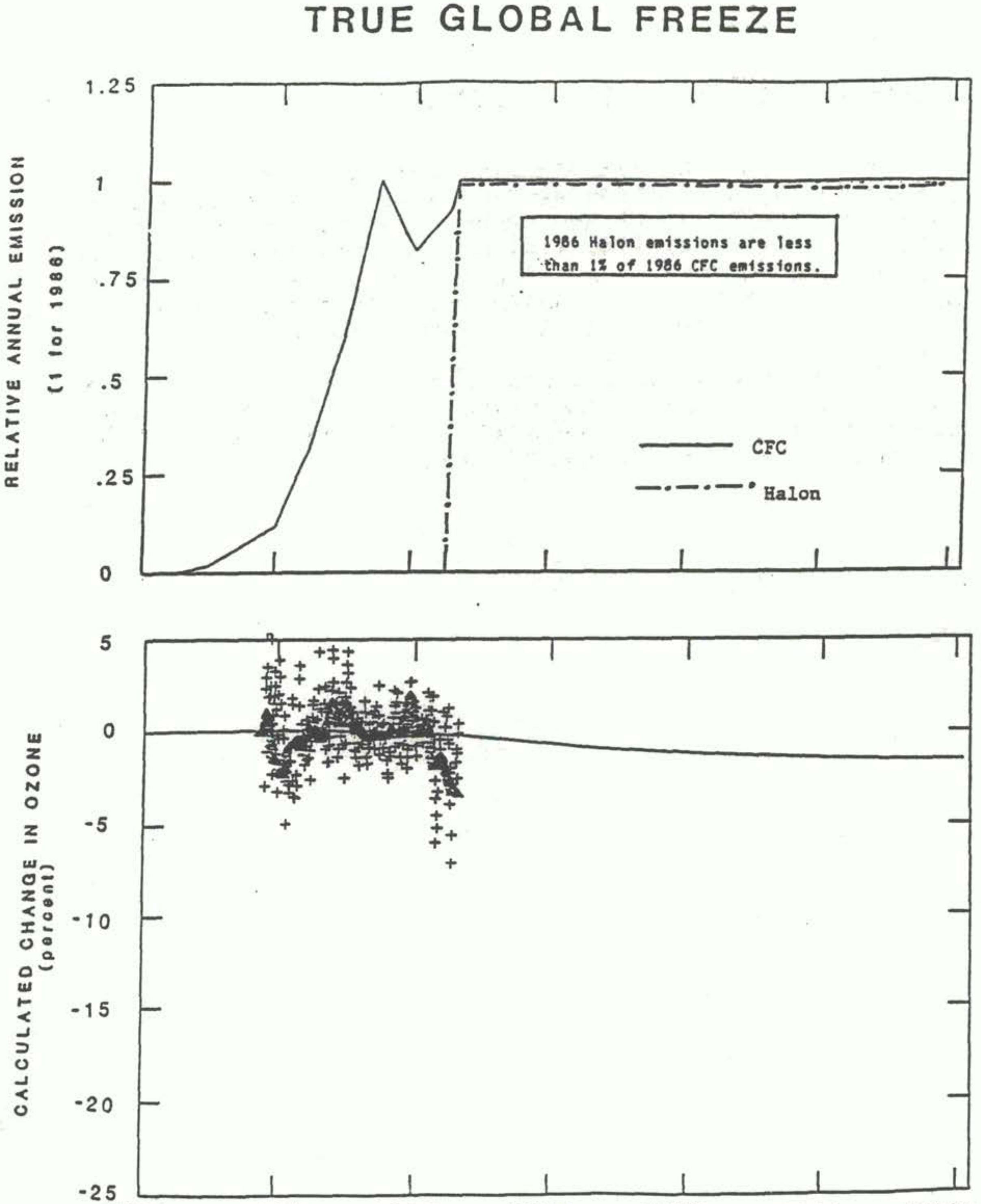

TRUE GLOBAL FREEZE
RELATIVE ANNUAL EMISSION
(1 for 1986)
1.25
1
.75
.5
.25
0
1986 Halon emissions are less than 1% of 1986 CFC emissions.
CFC
Halon
CALCULATED CHANGE IN OZONE
(percent)
5
0
-5
-10
-15
-20
-25
1940
1960
1980
2000
2020
2040
2060
YEAR

Figure 2 - Montreal Protocol Scenarios

The top graph presents relative annual emissions (emissions as a function of time divided by emissions in 1986) for the total of the Group I controlled substances (CFCs -11, 12, 113, 114, 115) and for the Halons over the period 1940 to 2060. Case 1 and Case 2 are described in Appendix I. Actual 1986 Halon emission rates are less than one percent of 1986 Group I emission rates.

The bottom graph presents the calculated percentage change in total ozone (calculated change in total ozone times 100 divided by calculated total ozone for 1940) for the emissions given in the top graph.

Figure 2

MONTREAL PROTOCOL SCENARIO

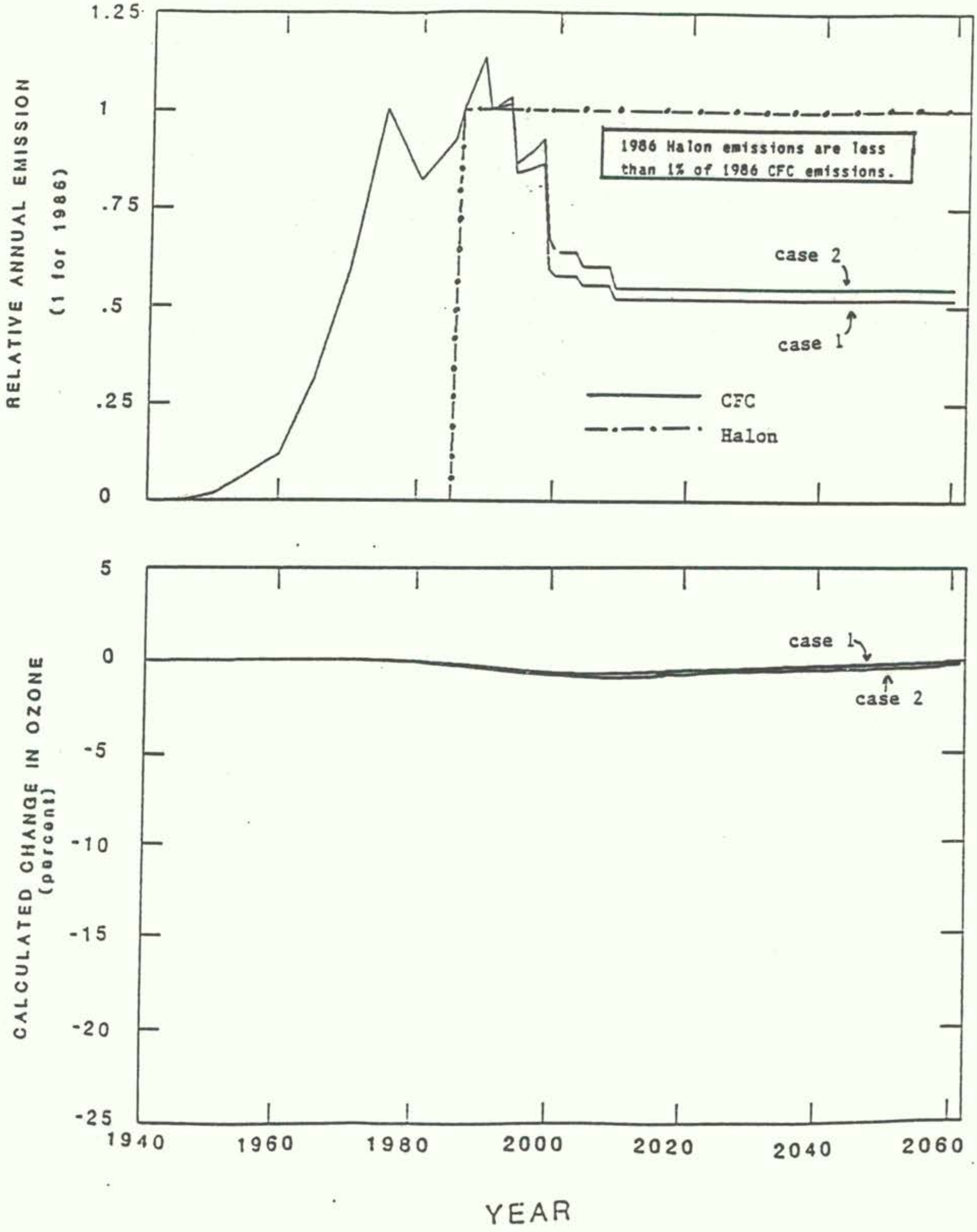


Figure 3 - Growth Scenario (Impossible Under Protocol)

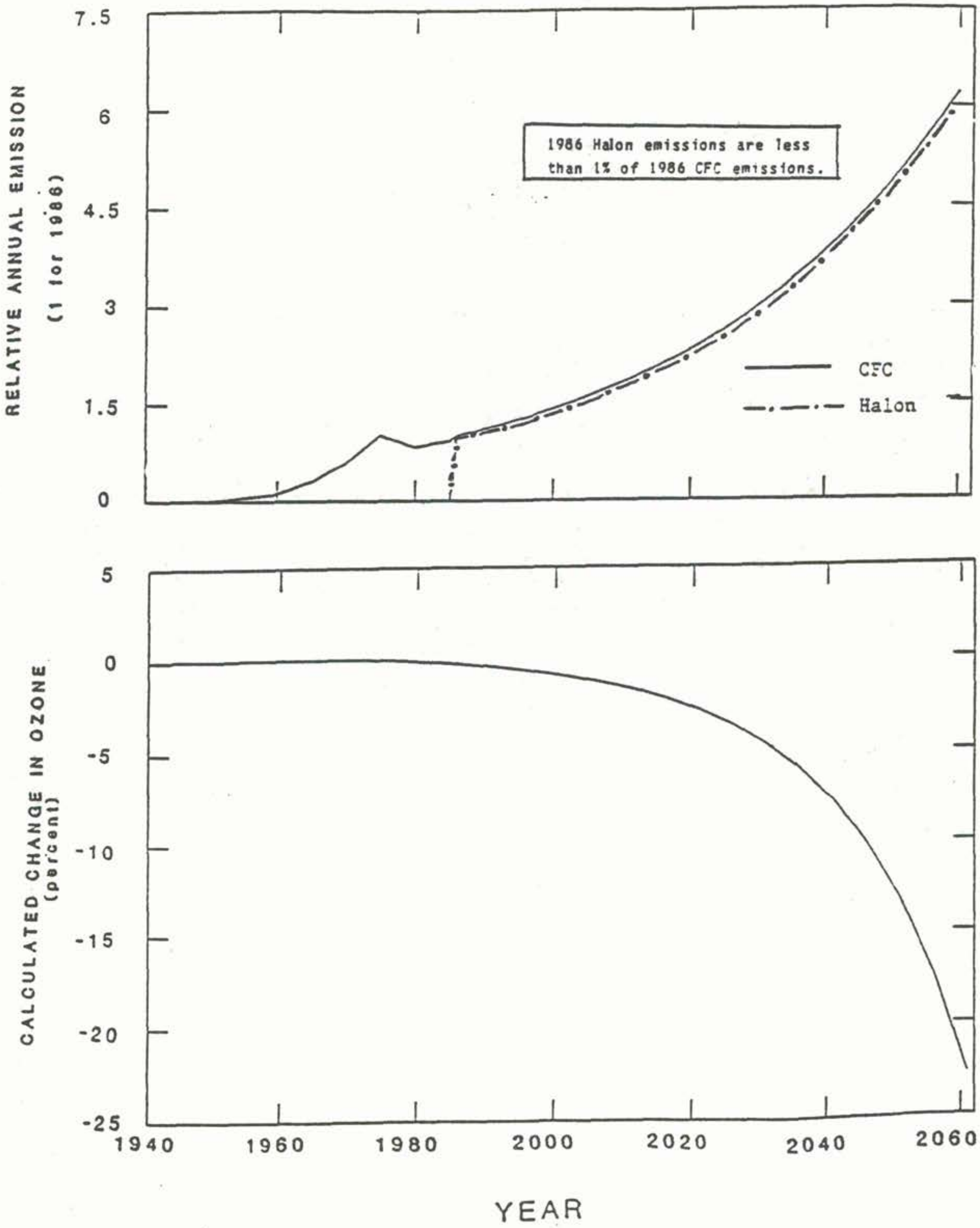
The top graph presents relative annual emissions (emissions as a function of time divided by emissions in 1986) for the total of the Group I controlled substances (CFCs -11, 12, 113, 114, 115) and for the Halons over the period 1940 to 2060. Actual 1986 Halon emission rates are less than one percent of 1986 Group I emission rates.

The bottom graph presents the calculated percentage change in total ozone (calculated change in total ozone times 100 divided by calculated total ozone to 1940) for the emissions presented in the top graph.

Figure 3

GROWTH SCENARIO

(Impossible Under Protocol)



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ENVIRONMENTAL PROGRESS REQUIRES COOPERATION

BY RICHARD BARNETT
CHAIRMAN
ALLIANCE FOR RESPONSIBLE CFC POLICY

Good Afternoon:

I am pleased to represent the Alliance for Responsible CFC Policy at this First North American Conference on preparing for climate change -- a cooperative approach.

The timing for this conference is perfect as we bask in the glory of the Montreal Protocol for the protection of the stratospheric ozone layer. My comments will focus on three areas: The Protocol, the implementation of the Protocol, how to improve our ability to work together in the future, and a critique of the process we have just gone through.

On September 16, 1986, the Alliance for Responsible CFC Policy issued a policy statement calling for the negotiation of an international agreement to limit the rate of growth of chlorofluorocarbon production capacity, the establishment of industry efforts to reduce CFC emissions through conservation and recycling, the pursuit of research and development of alternative CFC compounds and emissions reducing technologies and processes, and the continued research of the effect of CFCs in the atmosphere.

That policy statement was developed after a thoughtful review of the available scientific information and assessment of the policies necessary to protect the environment as well as the quality of life in the United States and elsewhere. Alliance members, through their Board of Directors, were concerned that the potential for a significant environmental risk existed if the rate of emissions of CFC compounds were to grow uncontrolled well into the next century.

This policy statement came only after great anguish and a strong industry assessment of the available scientific evidence which convinced industry scientists that we must take action and manage a future potential problem. Without this policy statement, industry would not have been a player in the game, but would have been relegated to the position of obstacle. I also might add that there remains some doubters and very reluctant industry participants. I'll talk more about why later.

The Alliance believed then, and still believes, that the current level of use of CFCs presents no significant risk to health or the environment. Further, it was our belief that a global process, and a global agreement, was necessary if we were to successfully address the environmental concerns and also address the economic concerns as we chart a course for a reasonable transition into new CFCs or CFC utilizing technologies.

Based on our current scientific understanding, the Montreal Protocol provides a substantial margin of protection for the earth's ozone layer. As has been stated before, a true global freeze limits any changes in the ozone to within the range of natural variability that has been detected over the last 30 years. The Alliance remains concerned that the reduction schedule included in the agreement attempts to go too far, too fast. The reduction schedule could result in problems for consumers in the United States as we attempt the difficult transitions into new, but as yet in most cases, unavailable technologies and CFC compounds. Our current estimates of the cost of implementing the Protocol are in the range of $5-10 billion, or nearly equivalent to the cost of Superfund.

The Protocol has many good provisions as well. It has gained the broad coverage of CFC compounds and the Halons. It has gained broad participation of CFC user and producer nations, and establishes a process for ongoing scientific, economic and technological assessment that can be used to alter the provisions of the protocol. In a sense, this blueprint of an agreement also provides the mechanism for alterations and additions.

We hope and fully expect that the Protocol will be ratified by the United States Senate and by other countries so that the accord will take effect in 1989. It is significant as well that the first scheduled scientific assessment is also scheduled to begin at the same time.

The implementation of the Montreal Protocol here in the United States should be simple, fair and enforceable. In no way should EPA attempt to go outside the provisions of the Protocol. To the extent that the agreement attempts to establish a level playing field among world competitors, we must remain committed to the framework provided.

EPA's program should also meet several other criteria. The rules should:

- Encourage the development of CFC substitutes and emission control technologies;
- Be easily administered;
- Not single out a specific CFC product or user industry; and
- Minimize to the extent feasible through market forces the potential for adverse economic impacts on users as a result to the Protocol's supply reduction schedule.

This is a challenging task, but one that must be pursued if we are to remain faithful to the blueprint we have before us. The Alliance believes that this can be accomplished if the cooperative spirit among government, industries, and environmental organizations can be maintained.

Finally, what have we learned from this process will benefit other global environmental issues. The potential for significant accomplishment is great, but so is the potential for failure. Industry assesses environmental issues in a very pragmatic way.

We try to define thr problem, gather data, look for solutions, test the proposed solutions, and choose the solutions which cause the least damage and disruption. Environmentally focused groups seem to want to solve perceived problems and implement solutions to the perceived problem regardless of what other consequences are caused. Legislators seem to want to put the issue behind them with sweeping action, and settle the issue once and for all. If they create bigger problems, they too would be handled by more sweeping legislation.

This perceived polarization of positions makes true understanding and problem solving almost impossible. The Alliance's policy statement of September 16, 1986, enabled industry to minimize their polarization. Many one on one and group meetings helped us all maintain a flexible negotiating position which performed as a check and balance to improve everyone's understanding and derive an accpetable planned solution. In a word, don't polarize the process! Once any faction of the process takes an extreme biased position, they must protect that position and communications, uzderstanding and problem solving stops.

Today, however, we have reason to be optimistic and I hope that in the future we can say, to paraphrase Robert Frost, that when we "came upon two roads in a wood, we took the one less travelled by, and that has made all the difference.

Thank you.

****

Richard C. Barnett - Chairman of the Board

Richard C. Barnett was first elected Chairman of the CFC Alliance in December, 1985. He is Vice President and General Manager of Central Environmental Systems, Inc., a subsidiary business unit of York International Corporation. In addition, Mr. Barnett has responsibility for York Air Conditioning Ltd., York International's Canadian air conditioning business. Mr. Barnett joined Borg-Warner's York Division in 1978 as Executive Vice President for Unitary Products. He assumed responsibility for the Canadian operation in March 1981. In 1986, Borg-Warner spun off the air conditioning business to create an independent public company, York International Corporation, for which Mr. Barnett has general administrative and operating responsibility. Prior to joining Borg-Warner and York International Corporation, Mr. Barnett held several managerial and engineering positions in the unitary products area with General Electric. He holds a BS degree in Mechanical Engineering from Southern Methodist University.

ADAPTABILITY TO CLIMATE CHANGE: THE CASE OF THE MARINE ECONOMY OF ATLANTIC CANADA

by

Peter K. Stokoe
School for Resource and Environmental Studies
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INTRODUCTION

As part of its effort to assess the socioeconomic and policy implications of climate change for Canada, the Canadian Climate Program is sponsoring studies to identify the sensitivity of economic sectors and regions in Canada to large climate changes, in particular climate changes predicted from general circulation models for a doubling of carbon dioxide in the atmosphere. Phase 1 of such a study has recently been completed for the marine economy of the Atlantic Region of Canada (Figure 1), and we are now about to begin Phase 2 of this work.

This study focuses on five sectors of the marine economy: fisheries, marine transportation, energy development, coastal infrastructure, and tourism and recreation. The study is illustrative of the multiplicity of effects through which climate change could have impacts on an economy and region, and of the difficulty of planning for socioeconomic impacts when the magnitudes of these effects, and in many cases even their direction, are very uncertain.

Predicted Climate Change

General circulation models yield predictions of average annual temperature rises of about 4 degrees Centigrade in the Maritimes and Newfoundland and 4.7 degrees Centigrade in Labrador, with somewhat greater increases in the winter months. The predictions of changes in average annual precipitation are a slight decrease of 2-3% in the Maritimes and increases of 5.9% and 7.5% in Newfoundland and Labrador, respectively.

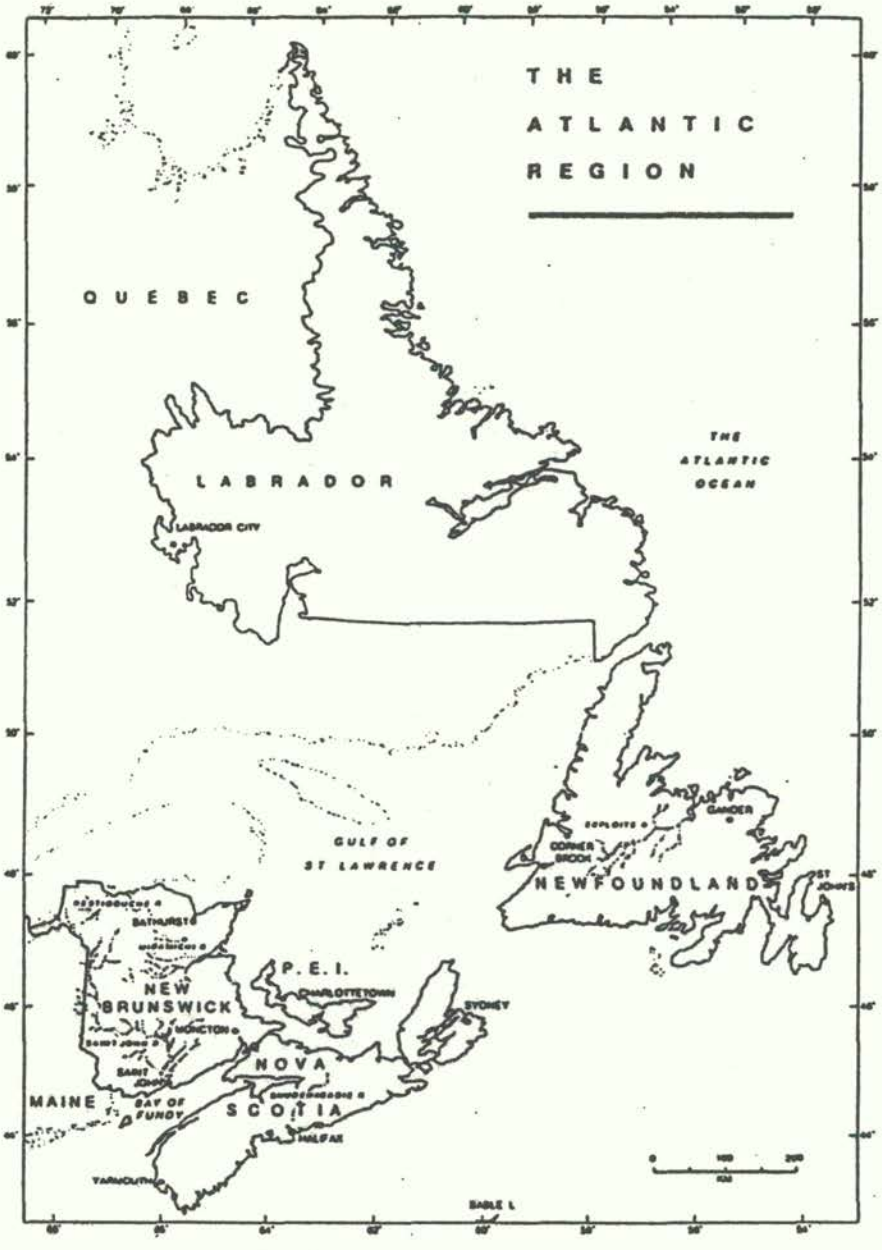

Fig. 1 - The Atlantic Region of Canada

Effects on the Marine Environment

Predictions of associated physical changes for the marine environment are:

(1) a rise in mean sea level (assumed for the purposes of this study to be of the order of 1 meter;
(2) an increase in average sea surface temperatures of 2-3 degrees Centigrade;
(3) a stronger Labrador Current with correspondingly increased influence in the Region;
(4) decreased surface salinity on the shelf areas;
(5) an absence of sea ice south of Labrador for most years, but
(6) no predictable changes in iceberg numbers and sizes.

Marine Biological Effects

While many of these marine environmental effects are generally conducive to increased primary productivity on the continental shelf, the important but indeterminate role of currents, fronts and upwellings leaves prediction of even the direction of change in primary productivity still uncertain. In any case, given a multitude of impacts on competing ecological effects, the progression of any change through complex food webs makes prediction of overall effects on individual fish species beyond present capabilities. However, it is expected from past observations that an increase in temperature would result in northerly extensions of marine animals.

The ways in which all of the foregoing biophysical changes impact on the sectors of the marine economy can be summarized by an "interaction matrix" (Figure 2).

Fisheries

Fish yield. While the overall impact of the various effects on fish stocks is beyond present predictive capability, a statistic indicating the current economic importance of the Atlantic Canadian fisheries is total annual landings in the capture fisheries, which have recently been approximately 1.2 million tons for a marketed value of $1.4 billion (Department of Fisheries and Oceans, 1985).

	Air temperatures	Precipitation	Wind	Humidity	Runoff and inland surface and subsurface water levels	Sea level	Sea ice and icebergs	Sea temperature and ocean currents/fronts	Storm frequency/intensity
FISHERIES:									
natural resource productivity					x		x	X	x
harvesting activity							X		x
aquaculture					x	x	x	X	x
MARINE TRANSPORTATION:									
sea transit							X		x
port accessibility						x	X		
ENERGY DEVELOPMENT:									
offshore oil and gas							X		x
tidal						X			
hydroelectric					X				
demand reduction	X								
COASTAL INFRASTRUCTURE						X			x
TOURISM AND RECREATION	X	x	x	x				x	x

X = impacts considered as major

x = impacts considered as less important

Fig. 2 - Matrix of interactions: climate change and sectors

Fishing activity. Apart from effects on fish stocks, climate change would have a major effect on fishing activity. The in-shore fishery (in which 85-90% of fishermen are employed) is currently restricted to half the year or less in much of the Region in part due directly to climate factors. Fishing activity off northeastern Newfoundland and in the Gulf of St. Lawrence is restricted by sea ice in the winter and spring. Some fisheries in these and other areas are also seasonally restricted due to fish migrations. Although the overall result of climate change for fish harvesting would also depend on changes in precipitation and prevalence of storms, a reduction in sea ice should allow extended harvesting seasons in many areas and easier exploitation of northern stocks (e.g., on the Labrador Shelf).

Aquaculture. While current annual aquacultural production of the order of $8 million is economically minor in comparison with production from the capture fisheries, this industry has recently entered a phase of rapid growth, doubling in production every 1-2 years. The direct effects of climate change would be favourable to this development. Warmer sea temperatures should be conducive to greater survivability, growth and reproductive success of most species, and these warmer temperatures as well as an absence of sea ice should allow new areas to be opened up to aquaculture for more species.

Marine Transportation

Marine transportation is important for trade within the Atlantic Region of Canada (especially between the mainland and the provinces of Prince Edward Island and Newfoundland), and for Canadian trade overseas. Marine transportation patterns in the Region could be most affected by changes in sea ice, and to a lesser extent by changes in sea level.

Canadian Coast Guard. The expected absence of sea ice in the Region under a 2xCO2 climate would relieve the current necessity of ice-breaking, for which the Coast Guard now incurs operating costs of about $20 million per year.

Ferry services. For the several major ferry services in the Region, absence of sea ice would allow savings from reduced operating costs due to less fuel consumption and damage and fewer delays, and reduced capital costs due to less need for ice-strengthened ferries. Decreased seasonality of some routes and increased accessibility of remote areas could also result in increased populations and increased tourist visitation, generating greater ferry traffic and related business opportunities.

Shipping. In comparison with other factors affecting the volume of cargo shipping and port activities, the direct impacts of climate change would be minor. A rise in sea level would allow ports to accommodate the trends toward larger ships with greater drafts. Reduction in ice would give a greater comparative advantage over Atlantic ports to the ports of Montreal on the St. Lawrence River and Churchill on Hudson Bay, which now, even with ice-breaking, can only be accessed during some parts of the year by ice-strengthened ships with additional operating costs and delays.

Energy Development

The components of energy development subject to major effects from climate change are offshore oil and gas, hydroelectric production and demand production (which may be augmented by conservation).

Offshore oil and gas. Sea ice and icebergs have major impacts on offshore oil and gas exploration and development on the northern Grand Banks and Labrador Shelf, and consequently their reduction would have major benefits for these activities. In the extreme ice year of 1984-85, there were 8952 hours of drilling downtime due to ice; measured in terms of the cost of over $100,000 per day for drilling at that time, this represented a loss of about $40 million.

Hydroelectricity. The Region's present hydroelectric production capacity is made up of about 5,600 MW in Labrador, 1,000 MW on the island of Newfoundland, 300 MW in Nova Scotia and 900 MW in New Brunswick. In each area, the potential (under current climate conditions) is roughly double these amounts. With climate model predictions of decreased runoff in the Maritimes and Newfoundland, and increased runoff in Labrador, net production capacity should increase, although the additional Labrador power would be more costly to deliver to markets than other power.

Demand reduction. Current average annual energy demand for space heating in the Atlantic Region is roughly 120 petajoules, which is equivalent to about 20 million barrels of oil or between $300 million and $450 million under current energy prices. This heating requirement corresponds to an average under current climate conditions of about 4500 heating degree-days in the populated areas of the Region.

The predicted climate change suggests a reduction of the order of 1200 heating degree-days, corresponding to annual savings in heating costs for current structures of the order of $80-120 million; some of these savings may be offset by additional costs for cooling in the summer.

Coastal Infrastructure

In evaluating the extent of loss and damage to coastal infrastructure from a sea level rise of about 1 meter over the next fifty years, it is useful to distinguish three categories of structures:

(1) existing permanent facilities such as: (a) urban waterfront land, (b) buildings with a life expectancy of more than 50-75 years, (c) breakwaters, (d) bridges and causeways, and (e) roads and railways, for which the losses would be of the order of hundreds of millions of dollars in each category, for a total loss of several billion dollars which would not be incurred without a rise in sea level, so that the costs of their replacement or reconstruction would be entirely attributable to sea level rise;

(2) existing non-permanent structures such as: (a) buildings with a life expectancy of 50-75 years or less, (b) fish plants, and (c) wharves, which would be subject to flooding from encroaching sea level rise, but which would normally be replaced anyway within the next 50-75 years at costs of the order of hundreds of millions of dollars in each category, and could be replaced with structures that take account of sea level change (within limits); and

(3) new structures or normal upgrading of existing infrastructure such as: (a) water and sewer systems, (b) urban and other new waterfront developments, (c) new bridges, causeways, and roads, and (d) Bay of Fundy tidal power which could be designed to take account of sea level rise at little additional cost if careful planning took this into account.

Tourism and Outdoor Recreation

Tourism yields revenues of over $1 billion per year in Atlantic Canada. Seventy to eighty percent of non-resident travel expenditures are in the 10-12 week summer tourist season.

Although the projected climate change would result in a longer summer and shorter winter, there may not be proportional increases in summer activities and expenditures and decreases in winter activities (e.g, skiing) and expenditures, due to non-climatic factors. For example, an extension of the summer tourist season may be limited by the currently established school vacation period of July and August, while the impact of a reduced winter season may be lessened if the "heavy use" winter holiday periods still allow winter activities.

Impacts on Coastal Communities

The impacts of climate change on each of these economic sectors become more significant when it is considered that they fall especially on a particularly vulnerable socioeconomic component in the Atlantic Region of Canada, namely small coastal communities (Figure 3). These communities are particularly vulnerable because their economies depend on these few, inter-related marine sectors.

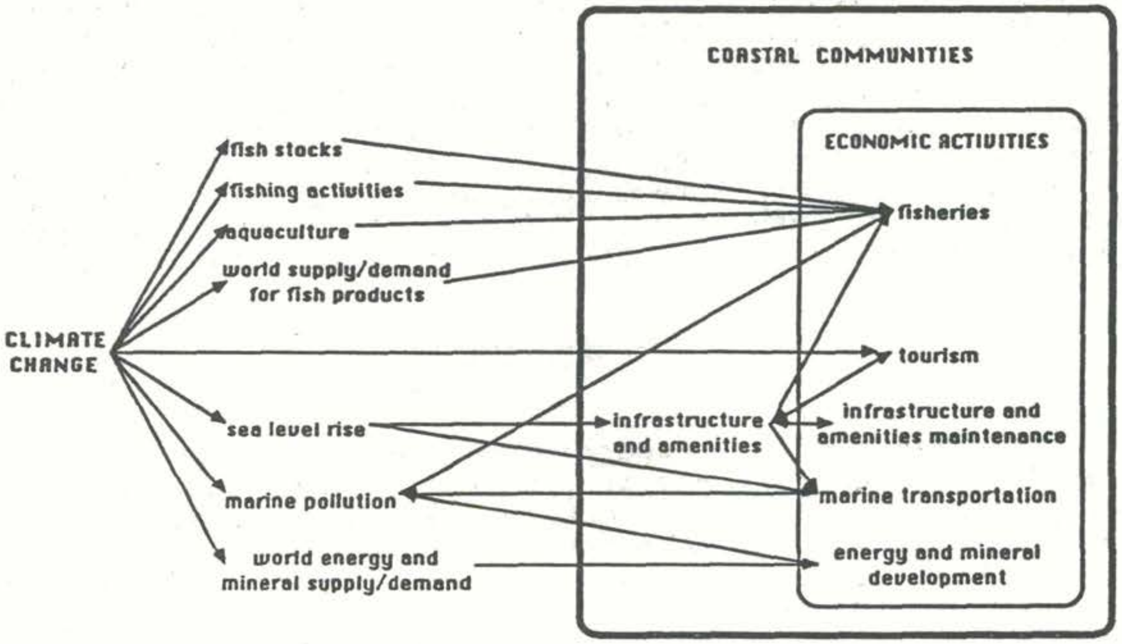

Fig. 3 - Climate change impacts on coastal communities

Quarter of the Region's population of just over two million, or over half a million, live in small coastal communities; more than half of the population of Newfoundland live in these communities.

Therefore, in Phase 2 of our study, we will be extending our analysis of impacts on economic sectors to an assessment of the implications of these impacts for the viability of coastal communities.

In considering the prospects for coastal communities, we are finding it useful to borrow the concept of "resilience" from ecological systems theory (Holling, 1973). History seems to indicate that, if we consider coastal communities as systems, their ability to survive has depended not on a capability to return to a stable equilibrium after predictable perturbations, but rather on a capacity for structural transformation, or resilience, in response to unexpected confluences of events. Paradoxically, planning oriented toward increasing the stability of a system in a familiar or expected environment can reduce its resilience toward the unexpected. Therefore, in planning for the viability of coastal communities through the climate changes which are now predicted, not only do we need to consider possible responses to the kinds of climate impacts suggested here, but recognizing our limited predictive capabilities, we also need to look to the social, economic and cultural resources which have allowed coastal communities to survive unexpected events in the past, and may continue to do so in the future (Lamson, 1986).

ACKNOWLEDGMENTS

Support for the research reported here from the Canadian Climate Program is gratefully acknowledged. The author would also like to acknowledge contributions to various parts of the research from M. Manzer and D. DeWolfe of Discovery Consultants Ltd. and S. Belford of P. Lane and Associates Ltd., as well as the cooperation of K. Frank and D. Scarratt of the Canadian Department of Fisheries and Oceans. Interpretation of the results in this presentation is the responsibility of the author.

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THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON ELECTRIC UTILITIES: PROJECT SUMMARY

Kenneth P. Linder and Michael J. Gibbs

ICF Incorporated

Project Overview

This paper summarizes the analytic approach and preliminary findings of a study jointly sponsored by the Edison Electric Institute, the Electric Power Research Institute, the New York State Energy Research and Development Authority, and the U.S. Environmental Protection Agency. The project examines the potential impacts of greenhouse-gas-induced climate change on the demand for electricity and electric utility planning and operations in two case studies.

The National Academy of Sciences reports that a change in the radiative properties of the Earth's atmosphere associated with a doubling of the concentration of atmospheric carbon dioxide (CO_2) will raise the Earth's temperature by 1.5°C to 4.5°C.[1] Increases in the atmospheric concentrations of CO_2 and other greenhouse gases (such as methane, chlorofluorocarbons, and nitrous oxide) have been measured,[2] and one recent estimate of the potential rate of warming that may result from these increased concentrations is a 1°C (1.8°F) increase in global temperature by 2000.[3]

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[1] J. Charney, Chairman, Climate Research Board, Carbon Dioxide and Climate: A Scientific Assessment, Washington, D.C., National Academy of Sciences Press, 1979.

[2] Atmospheric Ozone, WMO Global Ozone Research and Monitoring Project, Report No. 16, Geneva, Switzerland, 1986.

[3] J. Hansen, et al., "The Greenhouse Effect: Projections of Global Climate Change," in Effects of Changes in Stratospheric

Although the potential magnitude and rate of climate change remain uncertain, a recent meeting of scientists and policy makers in Villach, Austria, recommended that analyses of the potential implications of alternative climate change possibilities be undertaken in order to begin to assess the importance of climate change for man's activities.[4] This study of the potential implications of climate change for electric utility planning and operations is one such study.

Analysis of electric utility planning and operations is relevant for two reasons:

- The demand for and supply of electricity is sensitive to local weather conditions. Utility studies of customer demands have shown that daily and seasonal peak electric demands are determined in large part by demands for services provided by weather-sensitive appliances and equipment, principally heating and air conditioning equipment. Further, a substantial portion of seasonal and annual electric sales for many utilities also are determined by the use of such equipment. On the supply side, the operating efficiency of electric generation, transmission, and distribution equipment is affected directly by temperature and other weather variables. Also, stream flow (driven by precipitation and runoff into streams and lakes and evaporation from streams and lakes) affects the availability of hydropower which is an important source of electricity in certain regions of the U.S.
- The industry is very capital-intensive and has a long planning horizon, so that uncertainty in future demand and supply associated with potential changes in climate may pose substantial economic risks.

These two characteristics of electric utilities indicate that changes in climate may have an important influence on supply and demand for electricity within the time horizon considered for current investment decisions.

Ozone and Global Climate, J.G. Titus ed., U.S. EPA and UNEP, Washington, D.C., August 1986.

[4] Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, WMO-No. 661, Villach, Austria, 9-15 October 1985.

A case study approach was used to assess the potential impacts of climate change on utility planning and operations. Case study utility systems were selected in the Southeastern U.S. and New York State. By evaluating two diverse utility systems in detail, the relative importance of various climate change scenarios and different planning factors could be assessed. The experience gained from these detailed case studies is instructive for performing aggregate analyses of groups of geographically dispersed utilities.

The study focuses on the period 1986 to 2015. This 30-year period was chosen as representative of the time horizon of current utility planning decisions.

The approach used to perform the case studies is illustrated in Exhibit 1. The initial steps in the analysis are to (1) develop alternate climate change scenarios (i.e., changes in average seasonal temperatures for a particular area of the U.S. over time); and (2) estimate the sensitivity of electricity demand and supply to changes in weather conditions. This information is used to evaluate the potential implications of climate change for the future demand for and supply of electricity.

This demand and supply assessment is used with a set of utility planning assumptions as inputs to a utility planning model. This model is used to evaluate the implications of climate change for generating capacity requirements, fuel utilization, electricity production costs, and other utility planning factors. Climate change impacts are evaluated by comparing these planning model outputs (assuming climate change) with base case model outputs (assuming no climate change).

The utility planning assumptions were also varied to evaluate the economic risks associated with alternate planning decisions. Given that the extent and timing of future changes in climate are uncertain, utilities must make decisions today with imperfect climate-related information. The standard planning assumption implicitly employed today is that the future climate will be the same as the past climate. If the climate does change significantly within the time horizon of decisions that are based on this assumption, costly responses to changing conditions may be required in the future. By varying the planning assumptions, the potential costs and benefits of long-term planning for various amounts of climate change were evaluated.

SUMMARY OF CASE STUDY RESULTS

Exhibit 2 presents estimates of the changes in peak demand and total energy estimated for the Southeastern utility and for Upstate and Downstate New York utilities under "high" climate change assumptions, designated "temperature scenario C".[1] The table

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[1] Because of important uncertainties in modeling climate change, three alternate temperature change scenarios were developed for

EXHIBIT 1

ANALYTIC APPROACH

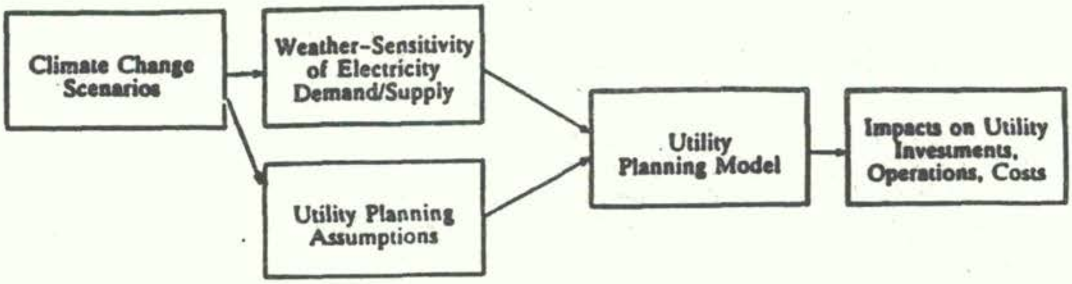

EXHIBIT 2

COMPARISON OF NEW YORK AND SOUTHEASTERN UTILITY CASE STUDIES: DEMAND SENSITIVITY (TEMPERATURE SCENARIO C)

New York	Change in Summer Temp. (°F)	Peak Sensitivity (%/°F)	Change in Peak Demand (%)	Change in Total Energy (%)
Upstate	1.46	0.66 to 1.47	0.96 to 2.14	-0.27 to -0.21
Downstate	1.46	1.51 to 2.77	2.20 to 4.04	0.49 to 1.04
System	1.46	1.19 to 2.27	1.74 to 3.32	0.13 to 0.45
Southeastern Utility	1.87	3.76	7.04	3.40

indicates that the estimated percent change in peak demand and electric energy requirements is greater for the Southeastern utility than for New York. This result is a product of: (1) higher estimated summer temperature changes in the Southeastern utility case study (1.87°F versus 1.46°F in New York); and (2) higher estimated weather-sensitivity coefficients (1.19 to 2.27 for New York versus 3.76 for the Southeastern utility). The estimates for Upstate and Downstate New York show the range of results obtained from two different modeling approaches (statistical and structural) used to estimate the weather-sensitivity of demand in the New York case studies. The two approaches differ in the data and level of detail used to estimate weather-sensitivity of demand.

It should be noted that the estimated sensitivity of peak demand to changes in temperature in Downstate New York is nearly as large as the peak-sensitivity estimated for the Southeastern utility. Given the same change in summer temperature, there would be similar estimates of percent change in peak demand in the two regions. Also, the substantially larger percentage change in total energy consumption for the Southeastern utility (3.4 percent versus 0.13 to 0.45 percent for New York) is related in large degree to the importance of air conditioning loads in all seasons for that utility. In New York air conditioning is almost exclusively a summertime use of electricity. In fact in Upstate New York, total energy requirements fall in response to the temperature increase (due to reduced winter heating loads).

Exhibit 3 indicates the estimated increase in generating capacity required by 2015 to maintain system reliability for the case study utilities. The "base requirements" shown in the table assume no climate change occurs. Increases in capacity requirements due to climate change are similar in the two regions. The range of additional capacity induced by climate change in New York is 746-1429 MW and is 1417 MW for the Southeastern utility, both under temperature scenario C assumptions. The percentage increases compared with base case additions during the period range from 10-19% in New York and is estimated as 21% for the Southeastern utility.

The potential impact of climate change on annual electricity production costs (annualized capital costs and annual fuel costs) for the case studies are summarized in Exhibit 4. Costs in New York range from $48 million to $241 million in 2015 (1985 dollars), depending upon the approach used to estimate weather-sensitivity of demand and upon the assumed impact of stream flow changes on the

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each case study region. These scenarios are designated as "A", "B", and "C", with temperature scenario "A" showing the smallest increase in average temperatures by 2015 and scenario "C" showing the largest increase. Similarly, in analyzing the potential impacts of climate change on stream flow in the Great Lakes Basin and, therefore, on hydroelectric generation in New York State, three alternate stream flow scenarios were developed. These are designated "X", "Y", and "Z", with "X" showing the smallest changes and "Z" showing the largest.

EXHIBIT 3

COMPARISON OF NEW YORK AND SOUTHEASTERN UTILITY CASE STUDIES: GENERATING CAPACITY REQUIREMENTS (TEMPERATURE SCENARIO C)

New York	Base Requirements (MW)	Additional Requirements Induced by Climate Change (MW, %)
Upstate	160	155 - 349
Downstate	7331	591 - 1080
System	7491	746 - 1429 (10%-19%)
Southeastern Utility	6749	1417 (21%)

EXHIBIT 4

COMPARISON OF NEW YORK AND SOUTHEASTERN UTILITY CASE STUDIES: IMPACT ON TOTAL ELECTRICITY PRODUCTION COSTS IN 2015* (TEMPERATURE SCENARIO C)

New York	Fuel Cost	Capital Cost	Total Cost
Upstate	-22 to +79	+5 to +12	-17 to +91
Downstate	+44 to +112	+21 to +38	+65 to +150
System	+22 to +191	+26 to +50	+48 to +241
Southeastern Utility	+217	+50	+267

* Millions of 1985 $

availability of hydroelectric generation. The cost implications of climate change impacts on hydro generation are significant in New York. The high case costs in 2015 for the Southeastern utility are similar in magnitude, $267 million (in 1985 dollars).

IMPLICATIONS OF FINDINGS

There are many uncertainties associated with developing estimates of potential climate change impacts. In the project we have addressed uncertainties in:

- climate modeling,
- weather-sensitivity modeling, and
- other economic, technological, and behavioral conditions.

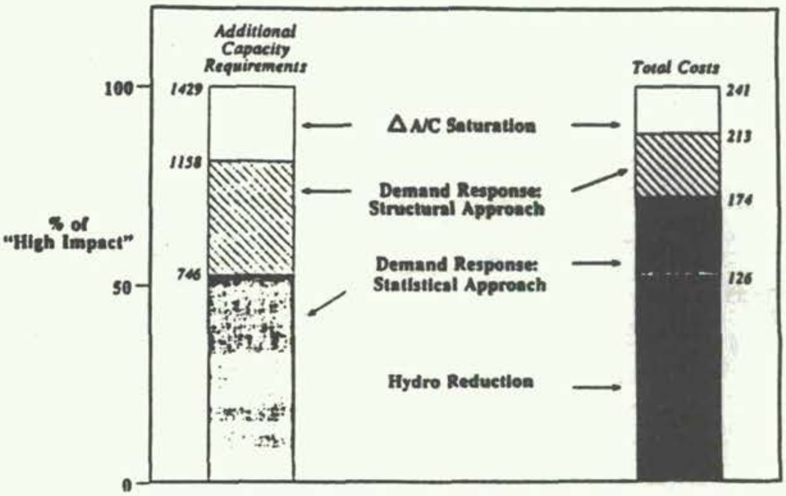
Because these uncertainties make it difficult to predict the future with precision, the results are driven by assumptions about these factors.

The relative contributions of key assumptions to the results are illustrated in Exhibit 5 for the New York State "High Impact" case. This case assumes:

- temperature scenario C (high),
- stream flow scenario Z (greatest change),
- weather-sensitivity estimated using the structural approach, and
- an increase in the saturation of residential air conditioning in response to climate change.

EXHIBIT 5

NEW YORK STATE
RELATIVE CONTRIBUTION OF KEY ASSUMPTIONS TO
"HIGH IMPACT" RESULTS
(2015)



Regarding the estimates of additional capacity requirements (left-hand bar), use of the data and assumptions in the statistical approach to modeling the weather-sensitivity of demand results in an estimate of 746 MW by 2015. Alternatively, use of the structural approach and assumptions of a constant saturation of air conditioning equipment results in an estimate of 1158 MW. The additional assumption that air conditioning saturation increases over time pushes the estimate to 1429 MW.

The right-hand bar illustrates the impact of these factors on total annual electricity production costs. This bar emphasizes the importance of the estimated effects of stream flow reduction on hydro generation, and the assumptions regarding the utilities' response to these changes. The substitution of oil generation and off-system electricity purchases for the reduction in hydropower availability accounts for over half (52%) of the estimated total cost impact of $241 million (in 1985$). Smaller <u>increments</u> are attributed to the statistical approach to demand response ($48 million), the structural approach to demand response ($39 million), and the assumption of increased air conditioning saturation ($28 million).

Although the results are sensitive to the assumptions about these factors, this situation is little different than forecasting demand, technological change, and customer response to utility conservation or marketing programs. These types of analyses, commonly conducted by utility planners, also involve substantial uncertainties and require many assumptions. Although not precise, the estimated impacts are judged to be reasonable. The findings indicate that the potential impacts of climate change on electric utilities are not insignificant and that these impacts may start to occur within the typical time frame of current utility planning studies and decisions.

Although the case studies have been conducted on different types of utility systems in different regions of the U.S., it is difficult to generalize to regions or the nation as a whole based solely on these results (e.g., consider the different results obtained for Upstate and Downstate New York). However, the analyses suggest the following general conclusions:

<u>Climate Change</u>

- The temperature change scenarios developed for the two case studies indicate that current general circulation model (GCM) estimates of potential regional climate change due to a doubling of atmospheric concentration of CO_2 are quite diverse.

- Climate model outputs indicate that the rate of climate change may be uneven over time, and may vary substantially from one location to another. This result is consistent with expectations regarding how the climate system would respond to increased greenhouse gas concentrations.

- In light of the diversity of the GCM results, and the relative inexperience of using GCMs to perform transient analyses, the climate change scenarios must not be considered to be forecasts. Although the scenarios reflect the diversity of current estimates, future climate change outside the range of estimates presented here cannot be ruled out.

Utility Impacts

- It appears that climate change will have greater direct impacts on the demand for electricity than on characteristics of the supply of electricity for most utility systems:

  -- The impacts resulting from demand response to climate change are more likely to be significant for utilities with large, summer, weather-sensitive (air conditioning) loads. This is true for regions in the southern U.S. where air conditioning saturation and utilization is high, and for urban areas in northern climate zones where the potential for increased air conditioning saturation is high. Because of the nature and patterns of these weather-sensitive loads, response to climate change is likely to have greater impacts on peak demand (capacity requirements) than on energy consumption (generation requirements).

  -- The order of magnitude of temperature changes examined here is unlikely to have significant impacts on the effective capacity or operating efficiency of thermal generating units. However, there can be significant implications for utilities where hydro is an important source of generation. As indicated by the New York case studies, hydro generation is critical for some utilities, and the potential planning uncertainties associated with possible climate change-induced stream flow changes are large.

- We have found that the utility capacity and cost implications of climate change potentially are significant. In the two case study analyses (1) generating capacity additions induced by climate change are on the order of 10-20% of base case (i.e., no climate change) additions through 2015 under scenario C temperature change assumptions (the highest case examined), and (2) annualized capital costs and annual fuel and O&M costs induced by climate change exceed $200 million (1985 dollars) in 2015. Because of long lead-times and the capital intensity of the most efficient electric generating units, there are economic benefits associated with being able to anticipate climate change correctly. The magnitude of the potential cost savings depends on the base case planning assumptions, and in these two case studies may be as high as $50 million per year (1985 dollars) by 2015.

- Utility planners should start now to consider climate change as a factor affecting their planning analyses and decisions. Large impacts are not imminent, but the importance of climate change impacts for utility planning is likely to increase over time. Climate change is likely to increase the uncertainties utility planners must face and to interact with other issues they must address, including:

  -- the level and patterns of future electric demands,

  -- the availability and mix of future generating resources, and

  -- investment and financial planning.

IMPLICATIONS OF CLIMATE CHANGE FOR ENVIRONMENTAL POLICY MAKING

Richard D. Morgenstern
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The prospect of global warming and climate change could require environmental policy makers to face two distinctly different types of decisions: (1) whether and how to limit anthropogenic changes in the atmosphere; and (2) whether to react to changes in climate as they happen or prepare for them before they occur. Recognizing these two aspects of the issue, Congress has recently asked EPA to prepare two reports on the greenhouse effect, which will be completed by the end of 1988. The first report will examine options for "stabilizing" the concentration of greenhouse gases; the second will examine the environmental impacts of global warming.

Since its inception, EPA has been in the business of regulating emissions of harmful air pollutants. However, with respect to the greenhouse effect, there simply has not been the social consensus necessary for creation of a regulatory program to reduce emissions.[1] For this reason, until recently, virtually all of EPA's work on the greenhouse effect has been concerned with adapting to the consequences of global warming, particularly sea level rise.

There is an emerging consensus that the global warming could result in a rise in sea level on the order of two to seven feet by 2100. (Dean et al. 1987; Meier et al. 1985; Hoffman et al. 1983). Such a rise would inundate low lying areas, erode beaches, exacerbate flooding in coastal areas, and increase the salinity of rivers, bays, and aquifers. There is no doubt that if this rise takes place, we will eventually have to change the way we manage our coastal environments. The question is whether there is anything that we need to do today?

Although coastal structures are not immediately threatened by the rate of sea level rise that is expected, there is reason to believe that measures should be taken today to protect shorelines (Titus 1986). As sea level rises, coastal wetlands and beaches will be inundated and eroded. In undeveloped areas, this presents no problem because new wetlands and beaches would form inland. But in developed areas, if people protect buildings from the sea with bulkheads and other structures, the natural shorelines could be replaced by armored shorelines. Along the densely developed recreational beaches, this will probably not happen because it is only slightly more expensive to restore the beach by pumping in sand from offshore, and there is ample financial incentive to keep the beach. But along the muddy wetland shores, the property owners generally have no similar financial incentive to restore the marshes; many would be happier with a bulkhead to which they might tie up a boat. Nevertheless, to the society at large, keeping our wetlands is important.

One option to preserve areas for future wetland creation would be to extend existing institutions that prevent building on wetlands to also include the inland areas onto which wetlands might migrate in the future. However, this would almost certainly be considered a taking that would require compensation, i.e. buying up most vacant coastal lowlands. This could be expensive, and uncertainties regarding how much the sea will rise would make it difficult to determine how much land actually needs to be withdrawn. On the other hand, simply developing areas without regard to future sea level rise could imply even greater costs because wetland protection would eventually require purchases of land and structures, costs that might be prohibitive.

A third option is to enact policies that allow coastal lands to be developed but with the understanding that if and when sea level rises enough to inundate and erode a property, the property will revert to nature, starting 75 years hence. Titus argues that this option is justified even today because (1) if it turns out that sea level doesn't rise, no resources will have been wasted in preparing for it; (2) as new information becomes available, land markets can rationally incorporate the new information; and (3) it protects wetlands without requiring large government expenditures; and (4) it gets around the "taking" issue because the present value of the losing the land at least 75 years hence is "de minimus", i.e. a tiny fraction of the property value. The idea could be implemented either by putting it on the deeds of coastal lands or as a permit condition for new development.

Recently, the State of Maine (1987) has approved regulations to implement this principle as part of its coastal management program, to protect both beaches and wetlands. The proposal states that houses are presumed to be movable. Anyone wanting to erect a building that is obviously not movable, such as a hotel or condominium, would have to show that even if sea level rises three feet, the building would not get in the way of natural wetlands or dunes.

The Maine approach essentially says that human activities have to get out of the way of the ocean, and that the individual property owner who constructs near the shore must take on the necessary expenses to prevent the structure from interfering with natural processes. If sea level rises, natural shoreline environments will be protected; if it does not rise, the only extra cost is the development of the contingency plan that did not have to be implemented.

The Maine proposal is the most significant instance of an environmental protection office preparing for future global warming. Nevertheless, climate change may require structures to be removed from other areas, such as potential reservoir sites, riverine flood plains, and critical ecosystems shifting north or "up the mountain." The same land-use planning principles may apply there as well.

The principle of requiring private parties rather than the government to bear the risks of future climate change is also likely to have broad applicability. As long as private parties bear the risks, new information on climate change can be efficiently incorporated into decisions; by contrast, if the government is expected to undertake the risk, the market can not use climate change information as efficiently because decisions will be more driven by what people expect the government to do. If the government is likely to take on the risk, there is little reason for a farmer to be cautious about buying farmland that will have to be irrigated or for a homebuyer to be careful about a house near a floodplain. But if individuals must take on the risk themselves, they will incorporate this information into land prices, and prepare when it becomes cost-effective to do so.

It is not yet clear when or whether it will be necessary for governments to undertake measures in response to the prospect of global warming. It seems clear to me, however, that it is already appropriate to make sure that governmental institutions do not inadvertently prevent the private sector from responding on its own.

NOTE AND REFERENCES

Note

1. A treaty has been signed to limit worldwide emissions of CFCs, a greenhouse gas, but concerns over depletion of stratospheric ozone was the primary motivator for that treaty.)

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DOES NEPA PROVIDE A MEANS OF ADDRESSING CLIMATE CHANGE?

William F. Pedersen, Jr.

I. The National Environmental Policy Act ("NEPA"), 42 U.S.C. 4321 et seq., was the first major statute enacted during the modern environmental era. In sweeping terms, it declares, as a national policy, the use of "all practicable means and measures" to "create and maintain conditions under which man and nature can exist in productive harmony." 42 U.S.C. 4331. It calls for the evaluation of each major new federal project to determine "the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity." 42 U.S.C. 4332.

Facing a statute couched in such sweeping and ambitious terms, one's first question is likely to be, "How could this statute not cover an environmental development as pervasive and important as climate change?"

II. A. This is true to some extent. If there were to be a major new federal program--for example, a synfuels program--whose effects would bear on climate change, NEPA without question would require an assessment of the climate change aspects of that program.

B. The problem is that we're beyond that point. It isn't our new activities, but our existing activities that are altering the climate. It is quite clear that NEPA only applies to new actions. Much ingenuity has been expended in past attempts to use NEPA to force reexamination of existing patterns of behavior that damage the environment, but they have never worked. The principle that inaction is not subject to NEPA has now been codified in regulations issued by the Council on Environmental Quality which state that failure to act is only subject to NEPA review to the extent it constitutes agency "action" reviewable in the courts. 40 C.F.R. 1508.18. Without belaboring the fine legal points involved, very few controversies would fall into this category.

C. Even if existing programs as a whole do not fall under NEPA review, one might think that individual acts to carry out those programs might fall under it. And so they do to some degree. However, the pattern is fairly random, and in some ways, might even be the opposite of what a concern with climate change alone would dictate. Since NEPA only applies to federal actions, its applicability is often driven by the intensity of pre-existing Federal involvement in an action or an industry. Because of the way the Clean Air and Water Acts are written, and because coal-fired plants are not pervasively regulated by the federal government, new coal-fired generating stations can often be built without any NEPA review at all. This would be unthinkable for a new nuclear station, even though coal plants contribute far more to climate change than nuclear.

D. Many commenters have criticized environmental protection laws for their "incremental" nature. By that, these critics means the tendency to regulate new actions very strictly, which may have the effect of discouraging those new actions, while at the same time leaving relatively untouched past actions or patterns of actions that may be more environmentally damaging than the new actions. Indeed, these old actions might even be activities that the new actions would replace. Similarly, it is ironic to note that were the government to adopt a comprehensive program to respond to climate change, it would certainly require a NEPA statement. In the absence of such a program, however, the activities that are producing that change go unaddressed by NEPA.

III. A. If NEPA cannot be used to address the climatic consequences of existing actions, perhaps we can turn the analysis around. What about projects that might be affected by climate change? For example: Federal insurance of a sea coast development, federal construction of a seaside air base, federal licensing of a seaside nuclear plant. Does NEPA force consideration of climatic consequences here?

B. There is a threshold problem in saying that it does. NEPA was designed to address projects that will have a major effect on the environment. Here, the important thing about the project is that the environment will have a major effect on it. This is not quite what NEPA was designed to cover.

C. However, that logical point may not matter too much in the end. Major projects such as those listed will almost certainly require statements for other reasons, simply because of their size and immediate impact on their surroundings. It is totally clear that once an EIS is required for a project, all relevant factors bearing on that project must be discussed even if they would not have called for preparation of an EIS in the first place.

The CEQ regulations say, in so many words, that such statements must discuss "economic or social effects" even though these effects "are not intended by themselves to require preparation of an environmental impact statement." 40 C.F.R. 1508.14.

"Effect" in turn is defined to include "ecological . . . aesthetic, historic, cultural, economic, social or health, whether direct or indirect or cumulative." 40 C.F.R. 1508.8. These effects must be discussed even though the information bearing on them is incomplete or unavailable as long as they are supported by "credible scientific evidence." 40 C.F.R. 1502.22.

Against this regulatory framework, it is totally clear that the possibility that the project in question would be under water or threatened with submersion before the end of its useful life would qualify as an "effect" on the "human environment" warranting detailed discussion in the environmental impact statement.

I don't discount the possibility that an ingenious lawyer could find a purely environmental effect in the impact of sea level rise on such a project. For example, sea level rise might force a nuclear plant to shut down early with attendant environmental consequences. But that almost seems beside the point given the conclusiveness of the first argument.

IV. The history of NEPA shows that after its novelty wore off its usefulness was restricted to two major areas. It was a very effective way of stopping projects that someone didn't like. Often, these were projects with real environmental problems. Second, it serves an "agenda forcing" purpose in raising issues to public attention. It is quite possible that NEPA will serve both these purposes in the new area of climate change as public awareness of that issue advances. But it would be unrealistic to expect NEPA to produce the kind of substantive regulatory controls that it has not provided when addressing much smaller issues. It just wasn't designed to provide them.

"Park Preservation Strategies in a Warming World"

by Herman F. Cole and Raymond P. Curran[1]

My interest in climate change extends back to the early 1970's when predictions of a "greenhouse effect" warned of a general warming of the environment. This interest was rekindled after I read Paul Brodeur's article on stratospheric ozone depletion in the June 26, 1986 issue of New Yorker magazine.

Later, I ran across Bert Bolin's description of the atmospheric problem, in the 1986 Assessment of World Resources[2], as an international astmospheric issue. Predictions made in the 1970's were proving to be accurate; carbon dioxide concentration in the atmosphere and global temperatures were rising. Further, additional climate changes were likely to occur. I was forced to ponder where our poor old planet Earth was heading. Given these stresses, what is likely to happen to both people and natural life systems? In short, will we make it?

My professional bailiwick involves the six million acre Adirondack Park of northern New York State. Lands in this Park, of which our state is justifiably proud, have enjoyed an unparalleled history of state constitutional protection. In 1885, a provision in the New York State Constitution established a "forest preserve" on which the timber could not be taken, cut or sold, and was to be kept "forever wild" in trust for the citizens of the State. Continued protection and enhancement of the Adirondacks as a natural area/nature reserve continued after the creation of the Forest Preserve concept -- most notably by establishing an Adirondack Park by Act of the State Legislature in 1892.

The Park contains both State Forest Preserve land and private land. More recently, in 1971, the Adirondack Park Agency, of which I am the chairman, was established and handed a regulatory and long range planning responsibility for both the state and private lands within the Adirondack Park. Our Adirondack Park is 9,375 square miles in size (24,000 square kilometers) - slightly smaller in size then the State of Vermont. It is larger than any other state or National Park in the continental U.S. and contains the largest wilderness land area east of the Mississippi.

As is true for most other parks of this scale, the Adirondack Park was created to embrace a set of unique, natural and scenic qualities, which set the geographic area apart from others. The Adirondack Park is commonly perceived to exemplify beautiful clear lakes, scenic mountains, swift rivers and interspersed pastoral areas of human habitation. However, the Park is near extensive urban areas. In fact, it is within a day's drive of more than 55 million people. The Park is now considered a four season recreational area and is visited annually by several million people.

The Park is a refuge for many rare or special concern plant and animal species including bald eagles, golden eagles and peregrine falcon. The climate of the Park, severe because of its high elevations and latitude, provides the southern limit to the range of many species. The "alpine zones" found on the summits of 10 of the Adirondack's highest peaks are micro examples of the arctic tundra. Two forest types favored by the climate and physiography, the northern hardwoods and boreal red spruce/balsam fir types, are superlatively represented. The Park contains the largest tract (40,000 acres) of never cut northern hardwood forest in the biome. Nowhere else in the "laurentian mixed forest eco-region" are as many acres of the red spruce type protected in the wilderness category as there are in the Adirondack Park. In fact, other wilderness examples can be found only in New Hampshire.[3]

The Adirondack Park is ecologically significant. The preservation of natural diversity makes this park valuable as a storehouse for genetic material and as a living laboratory for the observation of natural ecosystems.

Against this background it would be useful for me to project my expectations - in a perfect future - for the management of the Adirondack Park.

- First, we should continue to see balanced use of state and private lands in a fashion that does not detract from the use of these lands for outdoor recreation.

- Second, the natural systems which have historically provided multiple benefits to the people of the State - that is, the forests, fish, game, water and other natural products - should continue to receive the protection necessary for their maintenance.

- Third, public and educational institutions should foster an increasing public awareness and appreciation for the natural, social and historic resources of the Park.

- Lastly, progress should be made in restoring lost species and in enhancing the Park's biologic diversity. The spectre of changing climate, identified by many experts at this conference, holds much in store for our natural preserves like the Adirondack Park. I don't pretend to be an expert in the atmospheric processes involved in climate change. But, based on what I've heard from others, the effects which will be most significant to North America and its Parks are as follow:

  a. drop in stratospheric ozone levels and increase in carbon dioxide levels;

b. rise in average global surface temperature 1 degree by 2,000 A.D. and 5 degrees by 2,050 A.D.;

c. radical changes in wind circulation and changes in rainfall distribution;

d. marked increases in sea level, increases in hurricanes and extensive shoreline retreat in coastal areas;

e. migration of food belts and desertification of currently usable land;

f. differential warming in the Arctic;

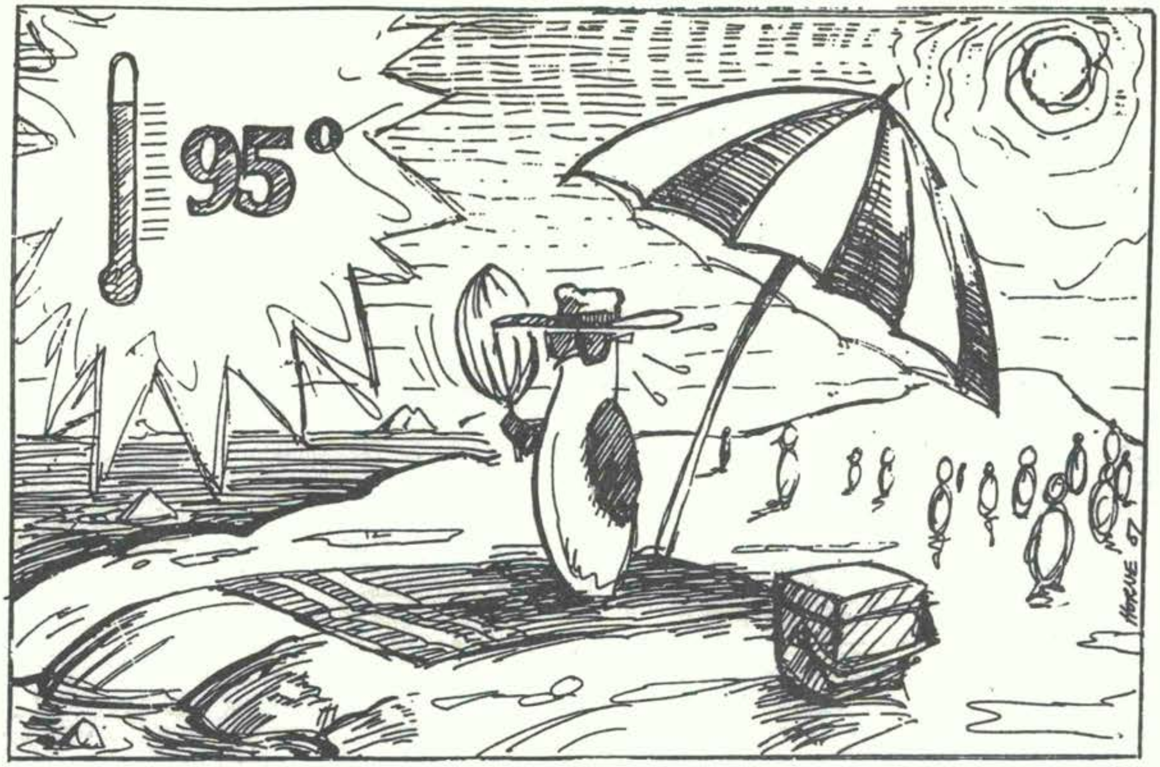
g. increased energy consumption, disruption of the existing energy infrastructure and increase in tropospheric pollutants including ozone, oxides and carbon monoxide.

These changes pose a grave danger to society as a whole-not just parks. Our health, our food supply and our shelter will be threatened. One might ask, "Why then should we be concerned with the effects in parks?" This is a legitimate question that I want to address.

As society seeks to adapt to climatic changes, the impacts caused by climate change will create pressure on all our land resources. The following graphics are meant to illustrate these land pressures. For the purpose of discussion, I have taken a little "poetic license" in showing the extent of each factor.

Melting ice packs and warming oceans may result in encroachment in coastal areas. Coupled with increased hurricanes and the amplification of storm tide surges, this encroachment would severly affect the Gulf and Eastern seaboard coast lines. In modified coastline areas, serious conflicts with existing development, to say the least of that conflict with natural areas, will occur.

Warming trends and redistribution of rainfall will lead to major changes in climate, biome shifts, migration of food belts and desertification of currently usable land. These changes will undoubtedly lead to land-use conflicts. As we can see, the location of freshwater supplies is closely linked to our major population centers. As the location of available water shifts, water supply systems will be rendered inadequate causing conflicts among water users. Also, conflicts will develop between urban and agricultural use of arable land. Low level atmospheric pollution by ozone, carbon monoxide and oxides will continue - especially down wind of industrialized areas. Depletion of stratospheric ozone will lead to severe ultraviolet radiation at higher elevations.



EXPECT MAJOR CHANGES IN GLOBAL WEATHER

SEA LEVEL RISE

Although a mountainous area such as the Adirondack Park may be spared from the effects of a single climatic change event, depending on the precise pattern, the outlook as a whole is for diverse and extensive effects. As civilization adjusts to climate changes, there will be increased pressure from society on all resources.

In order to develop preservation strategies for Park areas, we must first determine the effect of climate change on natural reserves and Park areas. In addition to the Adirondack Park, both the Everglades and Yosemite National Parks are useful for comparison when considering the effects of climate change. First, I'll briefly describe each Park:

The Everglades, known as the land of "grassy waters", encompass a diverse sub-tropical freshwater and wetland ecosystem. The Everglades are best known for its expansive grasslands, estuaries, mangroves, cypress islands and interspersed hammocks. Species of special concern found in these habitats include the manatee, eastern mountain lion, woodstork, roseate spoonbill, American crocodile and 40 tropical plants, including royal palm and gumbo limbo, found nowhere else. The Park, 5,665 square kilometers (1,400,000 acres) in size, is the largest combined land and water wilderness area in the East.

Surrounding the Park, Florida's population is expanding exponentially. The increase in fresh-water needs of this population and the historical diversion of water away from central Florida and the Everglades by massive public works projects have modified the freshwater flow that is so essential to maintaining the character of the Everglades. Draining has reduced the size of the historic Everglades by 35 percent and eliminated the natural variability of the fluctuating water regime.[4]

Manipulation of the water supply to the Everglades has resulted in unforseen environmental consequences. During a drought in 1985, water removals contributed to the drying of north and eastern portions of the Everglades and led to great concern that wildfires would seriously damage the area. On the other hand, too much water affects the nesting success of wading birds, such as the endangered woodstork. These birds rely on abundant food supplies created by the concentration of fish and invertebrates in freshwater pools, which shrink in size through the nesting season.

Yosemite is the patriarch of our nation's Parks. The second oldest park in the National Park system, it entered the system in 1890. Yosemite first achieved Park status in 1864 when Yosemite Valley was ceded to California by Congress as a public trust.

The 2,000 square kilometer park is visited by almost 3 million people annually; it is the most intensively used park in the National System. The unusual attractiveness of the mountainous area lies in its combination of scenic beauty including waterfalls, glaciers and giant sequoias. As with the other park examples, Yosemite encompasses a diverse biological heritage. This mountainous park includes five elevationally dependent life zones ranging from the hot, dry Upper Sonorran to the cool, moist Hudsonian and finally Arctic/Alpine life zone (at elevations above 11,000 feet).

Let's look at the range of possible specific affects in each Park area.

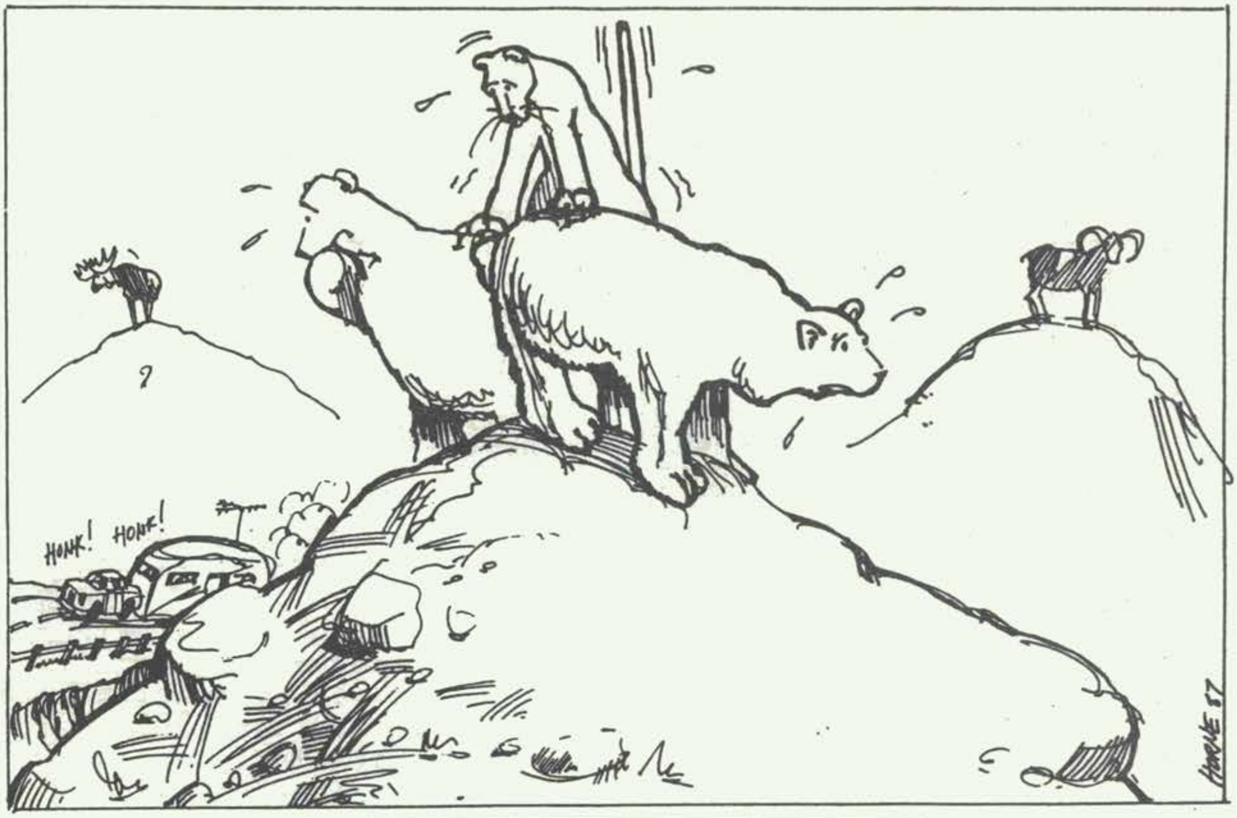
At Yosemite Park the stress of changing climate could produce both internal and external effects on the flora and fauna of the Park. Within the boundaries of the Park, changing climatic regimes might exceed the ecological tolerance of indigenous species forcing "migration" of species in the direction of more suitable conditions. Conceivably species adaptation could be accommodated in Yosemite by altitudinal migration with the life zones at either altitudinal extreme being replaced or severely modified. One can only envision this type of adaptation by making the great assumption that species colonization can occur at a rapid enough rate to keep up with climatic change.

However, natural reserves cannot be regarded in isolation of the surrounding landscape. Climate induced external factors, such as changing land uses and a trend toward increased disturbance of the landscape to meet resource needs, will undoubtedly change the biologic diversity within Yosemite Park.

I'll explain. A Park reserve, such as Yosemite, can be regarded as an island of leftover habitats surrounded by successional plant communities. The surrounding condition of the communities serves to isolate the island population making them prone to extinction even by the "normal" processes impinging on these ecosystems. Processes of concern include annual variation in climate, predation, disease or competition.

William Newmark hypothesized that Yosemite and Parks of its size or even larger were not of sufficient size at their creation to maintain the pre-establishment populations. In fact, he reported a 25 percent extinction rate of the mammalia species historically found in Yosemite, which was attributable to isolation of the species in the Park island.[5] Other theories, such as that presented by Peters and Darling, hypothesize that this island extinction process will be accentuated by stresses induced by climatic change.[6] In plain language, the Parks are barely large enough now to maintain their internal integrity; climate changes would aggravate the situation.

The important point is that loss of species diversity - the



WILL OUR PARK SPECIES SURVIVE
A CHANGING CLIMATE?

WATER USE CONFLICTS

very reason for creation of the Park in the first place - is the highly probable consequence of climate change.

Increased pressure for water resources, local atmospheric pollution and higher visitation rates are possible impacts on Yosemite from adjacent urban populations. Climatic warming might reduce the snow pack and dry up the rivers and waterfalls of the Yosemite valley. The result would be disturbance of the flow of these waters, thus severely affecting their scenic beauty. Wildfires that are so difficult to control in Northern California might become more common, due to increased evaporation, and overrun the Park. One is faced with questions like: What will be the effects of increased ultraviolet radiation at the higher elevations, up to 11,000 feet in Yosemite? Will the epidermal cells of organisms at these heights be subjected to mutations?

Let's move on to the Everglades. Because of the low elevation of the landscape relative to the sea level and the dramatic effect of changing freshwater flows, the changes in climate might have the most devastating affect on the Everglades. Freshwater will be in increasing demand for a variety of purposes. Water flows may be decreased by increased water withdrawal, by development and by shifting patterns of rainfall. Rising sea levels will cause the encroachment of saltwater into the freshwater systems and change the degree and timing of freshwater innundation. These are all processes that will reduce the colonization, reproduction and survival of many plant species. Increased storm surge elevation and storm activity will cause loss of vegetation as well as the destruction of Park facilities.

As the vegetational communities are altered, survival will depend on the ability of the communities to move and colonize habitats with more suitable climatic conditions. Similiar processes as in the Yosemite Island extinction will prevail. Additionally, physical barriers constructed to protect urban development from rising sea levels may serve as barriers to "wetland migration" to new suitable sites.

As in the Yosemite example, the Everglades would be faced with changes which strike at the very Park attributes and environment around which it was created.

Moving on to the Adirondacks, we might expect more severe fluctuations and increases in temperatures because of the continental nature of the climate, as well as increased tropospheric pollution because of the Park's proximity to urban centers. The incidence of ultra violet radiation at higher elevations will increase. Changes in temperatures and a general drying will cause stress to the plant communities and force shifts in vegetational composition. The expected result is species extinctions and loss of biologic diversity. For example, we could expect loss of the "alpine zones" on the mountain summits.

The juxtaposition of intensive development surrounding the Park presents a severe restriction to species movement. We will likely see increased pressure on the available lands within and surrounding the Park to provide food, shelter and energy. Water resources within the Park may be expected to accommodate not only New York, but other States' needs.

How should Park institutions respond to these changes? Perhaps a myopic approach would be to hand out sunglasses to shield the eyes of the unsuspecting fauna and tourist alike. We might also finance museums for our former nature reserve areas by selling ocean view lots in the Adirondack Park.

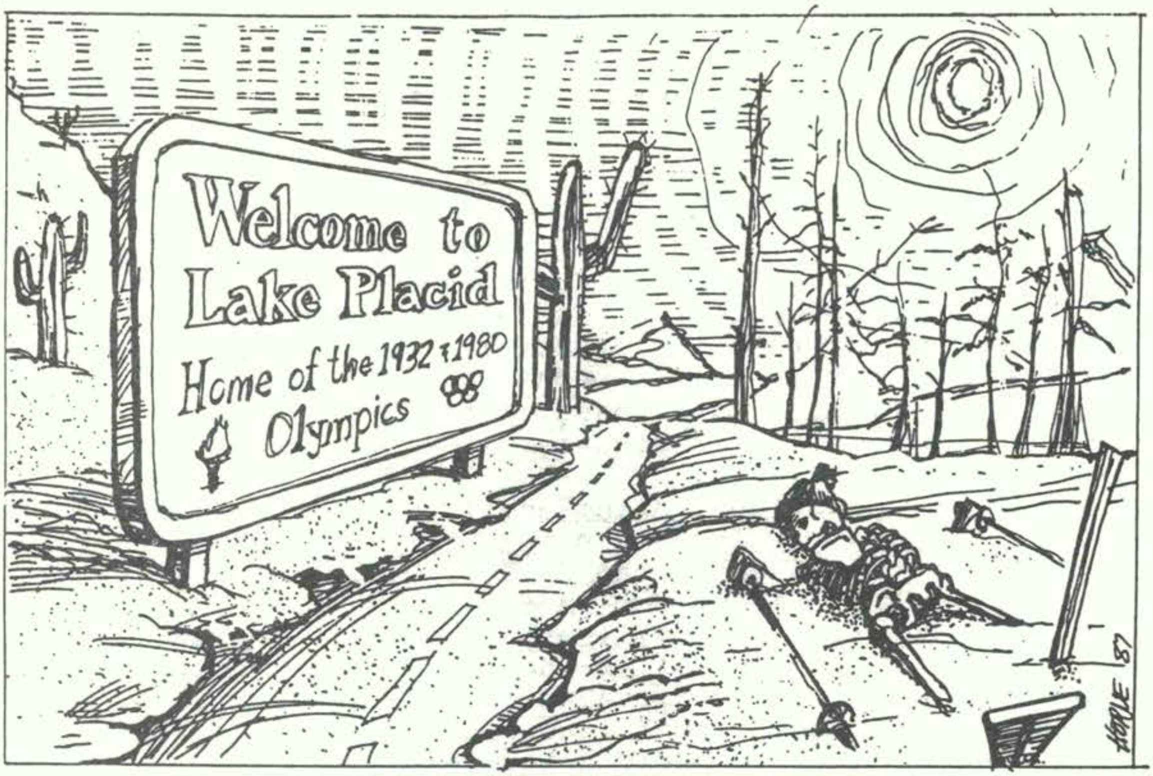
The best serious response would be a general societal change in manufacturing and in consumption, which would prevent or at least reduce the level of the climate change. We need safe energy alternatives to the use of fossil fuels and alternatives to the use of chloroflurocarbons (cfc's).

Despite accomplishments such as the September 6th signing of a global protocol to reduce cfc's in the atmosphere, there is reason to be pessimistic about the likely success of reducing the predicted global climate changes.

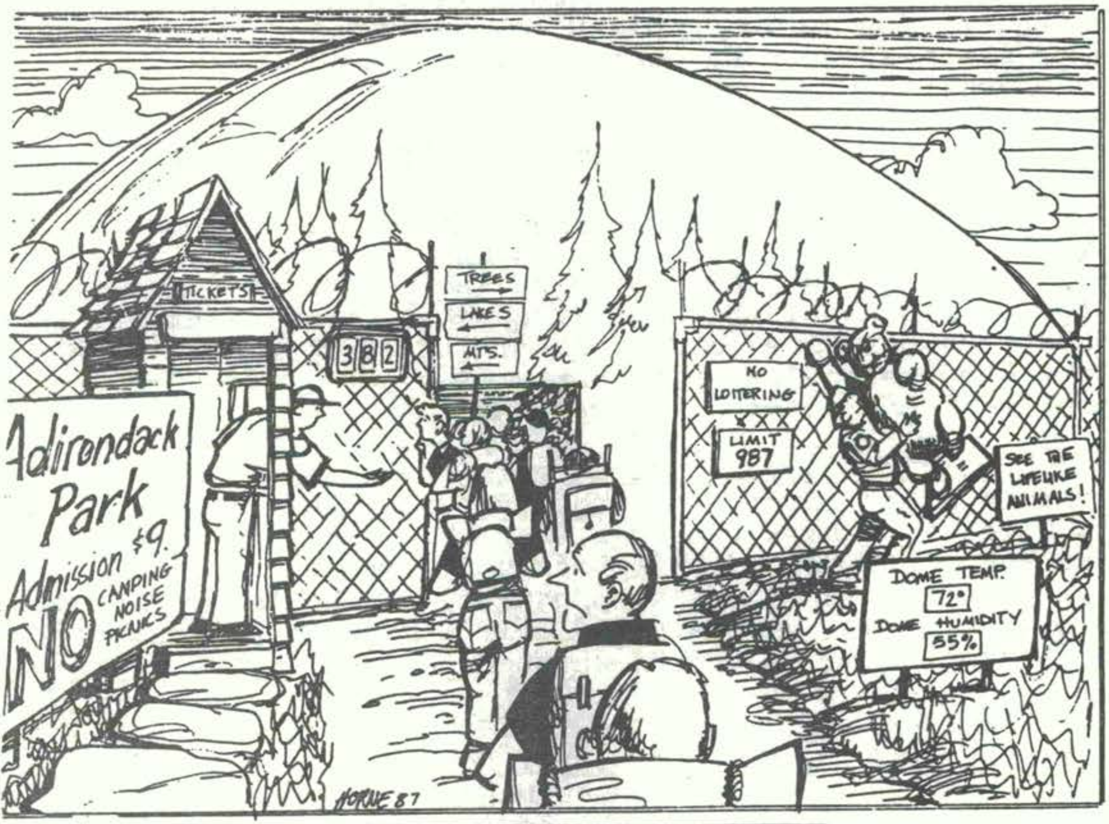
We are committed to a certain degree of warming and atmospheric change due to CO_2 and other greenhouse gas releases which have already taken place. Climatic warming will lag behind the atmospheric changes because the thermal mass of the oceans will help to absorb the heat.

Jessica Matthews has noted that the warming we are committed to in the next 45 years ahead is 3°C to 8°C above preindustrial temperatures. Further, Matthews states that this period of years is not a long time for certain societal responses to take place. As an example, this same timespan is comparable to the time it has taken new energy technologies to capture half of the global market.[7] Societal responses do lag behind the identification of problems. But, the inertia of institutions must be overcome and political changes negotiated if we are to prevent severe damages.

The pessimistic outlook toward resolving the global warming problem is further exacerbated when we look at this nation's response to acid precipitation. Little progress has been made by the U.S. government in correcting damage or preventing further impacts of acid rain. Cause and effect relationships have been demonstrated for the deteriorating conditions (and even complete loss of fish in some cases) in many Adirondack lakes due to acid precipitation. Also, impacts to forests -- loss of sugar maple, red spruce -- and changes to the soils of whole watersheds have been identified. Yet, there is no



THE GREAT LAKE PLACID DESERT



THE ADIRONDACK DOME – A MUSEUM OF OUR FORMER NATURE PRESERVES.

response from the Federal government other than to relegate the problem to the realm of future research because effects are considered speculative or of insignificant consequence.

With a view toward global climate change some people accept an adaptionist approach; they expect society to learn to live with the warming. This scenario would place nature preserves under a great deal of risk. Because society will be groping to find ways to accomodate its most basic needs, Parks would likely receive a low priority for protection. An emergency reaction will overlook parks; only careful planning will allow the protection needed to save these special areas. In order to protect our Parks, the response must be threefold:

First, we must understand the functioning of ecological systems involved within each nature reserve. While there are general predictions about the direction of global climatic changes, the specific effect on any one geographic area is unknown at this time and will probably baffle scientists. Our experience with ecosystems is that changes in environmental factors often have unpredicted disruptive results. In order to be in a position to respond in an intelligent and timely manner, we must understand the basic processes controlling an ecosystem and we must monitor the trends in that system. Our responses must be aimed at insulating nature preserve systems from the environmental pressures of global warming. We may be able to compensate for certain shifts in environmental parameters by using management techniques. However, in order to manage all of the changes caused by global warming, we must improve our knowledge of complex ecosystems.

Our second response must be to actively manage ecosystems to the extent needed to perpetuate them. Within our definition of wilderness we will need to accept the need for intervention in order to offset the damage caused by humans. Of course, this intervention should be kept at an absolute minimum and should perpetuate baseline conditions. This approach will require a major concession from proponents of a pure wilderness philosphy who regard any intervention as unacceptable.

Our third response must be in the area of education. The public must be informed of the true costs of climate change and its effects on Park reserves. At the same time, the value of Park resources should be emphasized. The development of environmental interpretive programs, aimed at all citizens, will help instill an awareness and will increase the size of the constituency that supports maintenance and protection of Parks.

A policy agenda such as that outlined in the World Resources Institute's The Global Possible[8] could be set forth to address the basic responses needed from society. In summary, our threefold response to the environmental challenges we face must be:

1) to better understand each and every ecological system within our natural preserves;

2) to actively manage it, and

3) to educate a constituency that will be prepared to pay the price for protection of nature reserves.

The alternative is a program of isolation and separation of our nature reserves from our global climate and its people. This, in my opinion, is not an achievable or desirable goal. Let us keep in mind an observation by John Muir, a 19th Century advocate for setting aside Park areas. He said:

"When we try to pick out anything by itself, we find that it is bound fast by a thousand invisible cords that cannot be broken to everything in the universe."[9]

Certainly our advancement of knowledge can only strengthen our recognition of the interdependence of all things.

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LIKELY EFFECTS OF CLIMATE CHANGE ON FISHERIES AND WETLANDS, WITH EMPHASIS ON THE GREAT LAKES

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CONTENTS

A. INTRODUCTION

Fish, as aquatic animals, are not immediately and directly affected by atmospheric temperature and precipitation, but rather by the effects of the latter in the aquatic habitat. Even first-order approximations of climate impact on fish must take into account how key hydrological features of relevant water masses are affected by climate, say as annual means, average seasonal regimes, maxima and minima, etc. Existing generalizations related to hydrological and other "natural" variables are sufficient for first approximations; refined assessments will depend in part on more precise assessments of hydrological and other environmental impacts by the relevant experts. But in addition to such a "natural chain" of events there will also be a "cultural chain". How will human activities, as they affect these waters, be modified as a result of climate change?

It may prove to be the case that the Great Lakes aquatic ecosystem will be affected relatively less intensely by climate change, through the "natural chain", than other large freshwater ecosystems of North America. Our paper might present a best case scenario, in that respect. But it may happen that impacts activated through the "cultural chain" may be quite intense in the Great Lakes Basin.

In our studies of the likely effects of climate change on the fish and fisheries of the Great Lakes through the "natural chain" of events we have started with first-order approximations based on generalizations that are broad, imprecise and that may appear to be simplistic. This approach is dictated in part by the approximate nature of climate predictions currently available, in part by the inadequacies of our present understanding about the effects of climate variables on fish, and in part by deliberate strategy. As we learn more, our assessments are being revised and refined. But the assessments need not inevitably become highly complicated; simplicity, sophistication and usefulness tend to go together, within an appropriate approach from a particularly relevant perspective.

So far we have concentrated more on the effects of change in temperature than in precipitation or other climatic variables. In the Great Lakes as such, temperature effects will likely be more important than precipitation effects. But in the fringing wetlands and in the streams of the watershed, both may be equally important. Certainly fish cannot persist on a dry streambed, and no species of the Great Lakes region has adaptive behaviour to burrow into bottom muds and "aestivate" through such periods, as lungfish are capable of doing in some African waters that dry out periodically.

We have not yet seriously considered the possibility that some effects of climate change may occur so rapidly or so erratically that the features of some stressful transition period may be more important ecologically and culturally than the nature of some altered quasi-steady state that may then follow such a transition. For example, a rapid turbulent transition might cause the extinction of some species or taxa while a slow smooth transition might not. In recent decades some events, related to Great Lakes fish and fisheries, occurred quite rapidly, such as the eutrophication of Lake Erie's Central Basin, the explosive invasion by smelt and alewife of Lake Michigan and the invasion by sea lamprey of Lake Superior. Ecologically, a number of unique taxa were extinguished. Had these changes occurred less rapidly, then the overall ecological and cultural impacts would likely have been less severe.

B. SOME EFFECTS ON FISH PRODUCTION AND YIELDS

In the comparative study of fish and fisheries of different freshwaters, as in fisheries limnology, climate belongs to one of at least four key macro-factors (Figure 1). In ecosystems like the Great Lakes, the various effects of the climatic factor interact and are affected by all the other macro-factors as that climatic factor actually influences fish and fisheries (1). Such an interactive reality is implied by the term ecosystem, of course.

Figure 2 provides a basis for a first approximation of effects of climate change on the fish and fishery (2). The points that fall on a particular iso-line all depend on the four macro-factors shown in Figure 1. The climatic variable used for Figure 1 is average annual air temperature near the surface. Each iso-line relates to a particular average annual temperature; the relevant expression (2) is $\mathrm{TEMP} = 20.0 \log_{10}\mathrm{MSY} - 13.69$. A point on an iso-line indicates the sum of the average annual optimal yields to the fishery of the fish species valued by the fishery, as an aggregate measure in units of mass per hectare. The aggregated optimal yield is for a hypothetical water mass which is approximately optimal with respect to the other three macro-factors, i.e. human practices, water body hydrography and hydrodynamics and fertility as related to the ecological needs of the native valued species. Various corrections can be made, based on quantitative expressions, for sub-optimality of various features of the macro-factors, i.e. the underlying relationship can be used for coarse-tuning to particular water bodies (3).

Some fisheries limnologists question whether air temperature has an important effect above and beyond insolation intensity, the latter as a driving variable for the photosynthesis that underlies ecological production and for the direct heating of water. The question is important in that regional air temperature but not insolation will change markedly with the greenhouse effect. Circumstantial evidence supports a strong role for air temperature, beyond mere insolation (4). Some integrated temperature features of larger water bodies and of deeper ground water appear to be more closely related to air

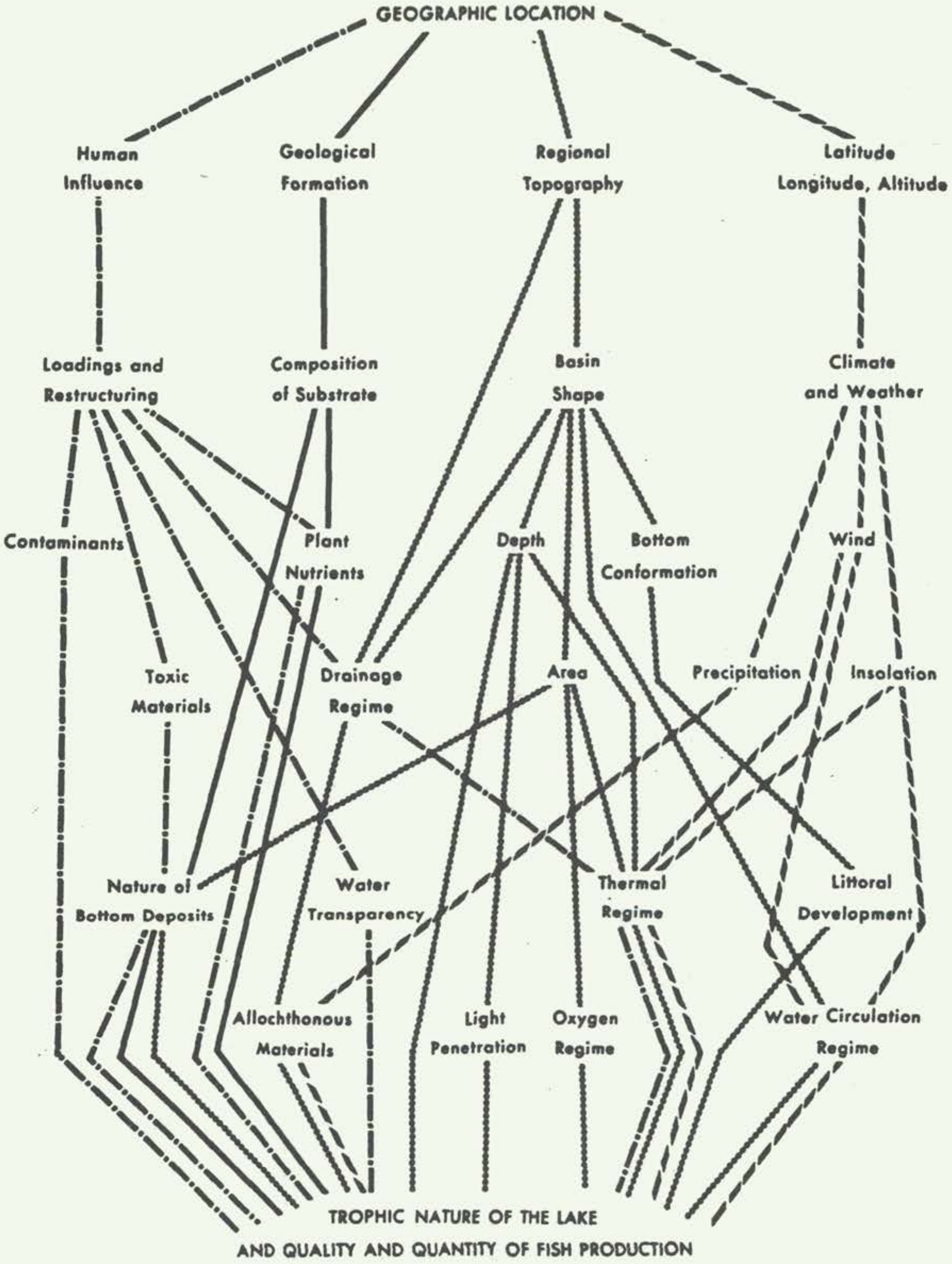

Figure 1. Various human and abiotic factors that influence the biotic characteristics of lakes, especially with respect to the ecological production of fish of various species (1).

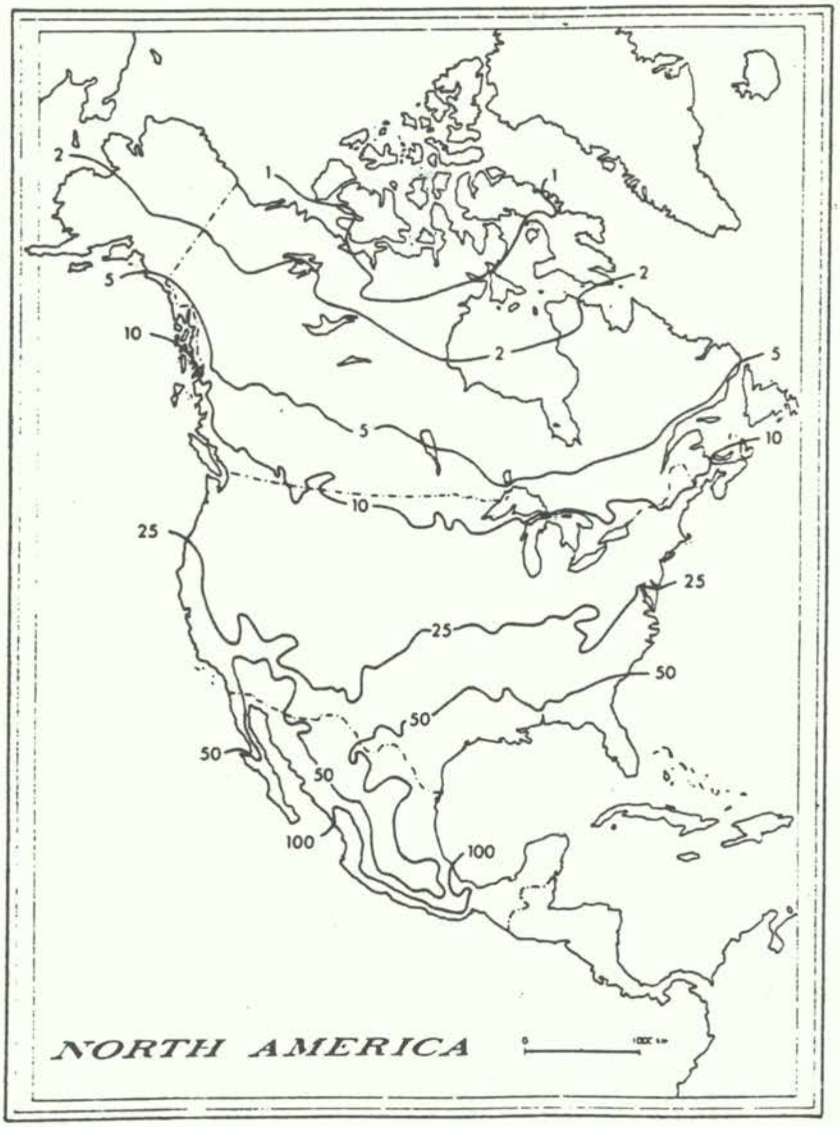

Figure 2. Iso-lines showing theoretical upper limits to maximum sustainable fish yield (expressed as kg/hectare·year) in North America (2). Localized altitudinal differences in mountainous areas, which are not depicted on the map, also would affect climatic patterns and potentialfish yields.

temperature patterns than to insolation patterns. With respect to temperature, there appear to be strong systemic interlinkages between surface water, groundwater and the overlying atmospheric or weather system, at least with respect to phenomena of ecological importance to fish.

If the scenarios of the atmospheric scientists adequately account for the systemic linkages indicated above, then we may ignore insolation and use their predicted average annual air temperatures in the appropriate quantitative relationship, on which Figure 2 is based, to estimate an effect on aggregated optimal yield. For every increase of 1 C°, optimal yields in aggregate should increase by 12%, and this effect will likely be geometric for increases greater than 1 C° (4). Thus climate warming will likely lead to increased annual production of the aggregate of valued fish species in the offshore Great Lakes waters, on the assumption or judgement that changes in precipitation will not strongly affect these offshore waters ecologically and that the impacts through the "cultural chain" will be weak.

A basic reason for increased production relates to the fact that fish are poikilothermic, i.e. their body temperatures approximate those of their habitat. A broad generalization of physiology and ecology states that the rate of metabolic and production processes in a poikilothermic species is a direct exponential function of temperature, within the range of temperature to which the species is well-adapted (5). But different species are adapted to different temperature ranges, and in particular have temperature optima that may be quite different. Species of the trout and salmon family prefer cold temperatures less than 20 °C, while perch family species prefer temperatures of 20 to 25 °C and bass family species above 25 °C, as rough approximations (6). Thus a change in the temperature regime of a water body will cause a change in the relative abundance of different species depending, in part, on how the climate warming changes the thermal structure of the water body. Generally in the Great Lakes the nearshore basses and perches may benefit more than the offshore salmons and trouts, ignoring effects on lake levels due to precipitation changes, and ignoring secondary cultural impacts.

Figure 3 shows relationships of several species to a measure of habitat as affected by temperature (7). From a study of how fish species distribute themselves to the thermal features of a water body, J.J. Magnuson and colleagues (8) inferred that the "thermal habitat niche" encompassed a fairly narrow range of temperatures that bracket the optimal for a species. The panels of Figure 3 are based on this inference and on another related inference (9) and show, by comparative analysis, that the larger the measure of near optimal habitat, through space and time within a year, the higher the production to a fishery of that

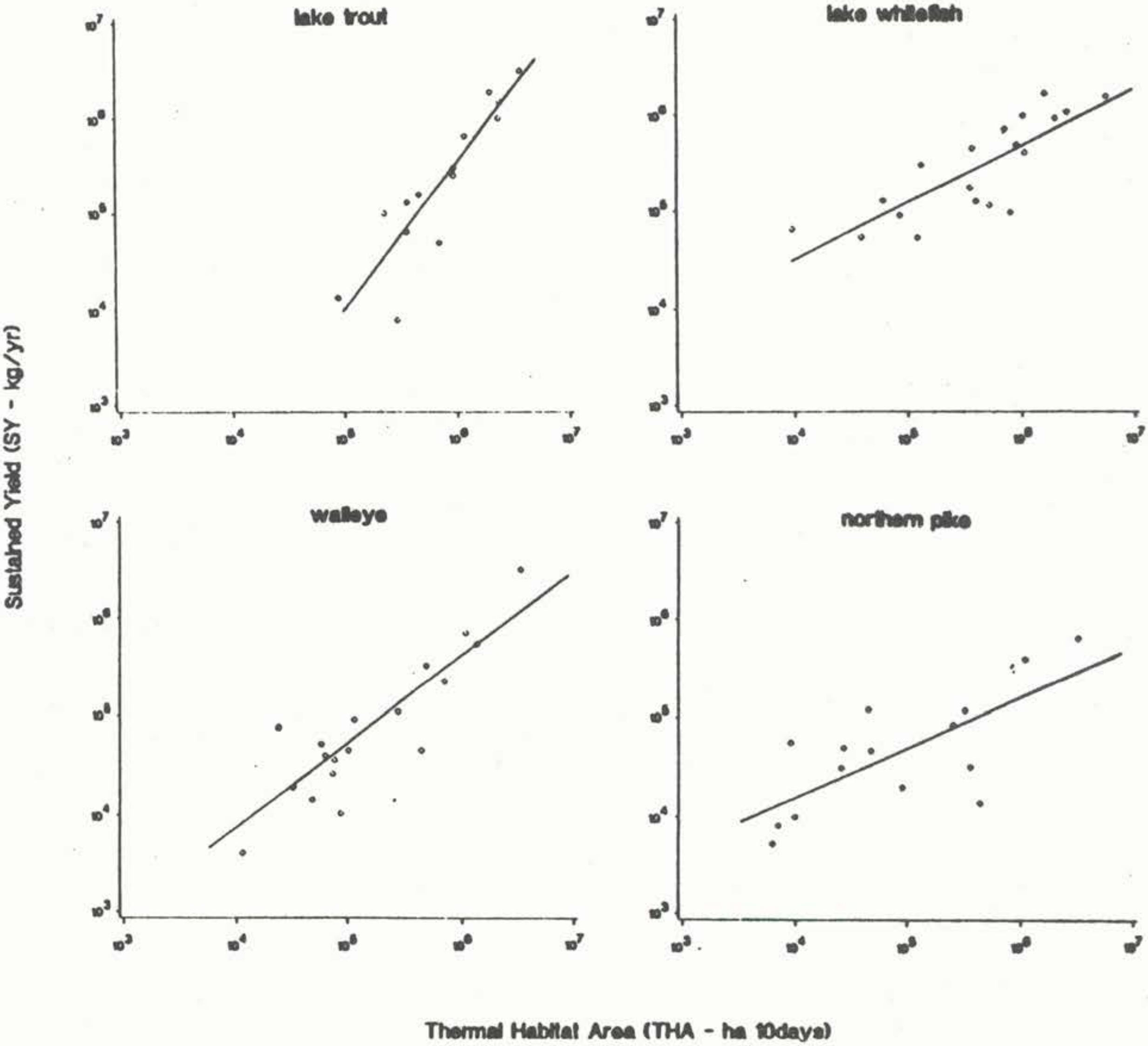

Figure 3. Plots of total sustained yield versus thermal habitat area for four valued fish species (7).

species.

In comparative studies, yields to a fishery from a particular species appear to be maximal (per unit of habitat disregarding thermal criteria) toward the mid-point of its latitudinal range. Small populations may occur in waters toward higher latitudes, - perhaps streams or protected bays may have thermally-optimal habitat near the surface for sufficient periods of time even if the offshore waters may not. Small populations at lower latitudes may resort to cooler deeper waters or cool spring-fed streams to escape dangerously high temperatures in summer. Moderately increased temperatures in a particular lake of the Great Lakes Region will likely suppress those species that exist toward the southerly edge of their range (e.g. salmonids) and favor those that now exist to the northerly edge of their range (e.g. centrarchids). Some species in lakes near the central part of their range will not be much affected, in that the thermal habitat may shift from a cool state below full potential to a warm state above it with no major change in productivity and relative abundance in the ecosystem (e.g. walleye in some of the larger bays in Lakes Huron and Michigan).

When the hydrologists will have assessed the impact of climate change on the seasonal thermal structure of the different water bodies we intend to use the relationships shown in Figure 3 to assess the impact of climate change on the potential productivity of different valued species in the different Great Lakes. This will provide first approximations for individual valued species; these numbers may then be aggregated and compared to the approximations obtained by applying the methodology related to Figure 2, above.

C. SOME EFFECTS ON FISH SPECIES DISTRIBUTION

In the preceeding section we focussed implicitly on the hydrological, especially hydrographic, determinants of fish production, as those hydrological determinants express the climate's thermal regime with respect to thermal habitat. Here we focus more on the geographic limits of the distributions of different species, as these relate, say, to the extinction of species in a water mass and to its invasion by non-native species.

A broad generalization holds that the "cold limit" of a species' geographical distribution (at higher latitudes and/or higher altitudes) is determined to a strong degree by the lack of thermally-optimal habitat in summer and/or the absence of "thermally-sufficient" water in winter. "Thermally-sufficient" here means that not all parts of the water mass fall to temperatures that are excessively cold to the species, i.e. there remain warm refugia even in the dead of winter. The deaths of individuals may not be due simply because the individuals do not experience some period of optimal temperature, or simply because they suffer excessively cold temperatures. Rather, when one or both of these conditions apply, the species cannot maintain its ecological role in the ecosystem. Individuals will be predisposed to die in excessive numbers of disease, starvation, predation, etc. and the species will not persist in such waters.

Long-term studies of smallmouth bass near the northerly limit of their distribution show that the relatively small young-of-the-year bass die of starvation-related causes during the first winter. Size attained in the first summer is strongly dependent on availability of a suitable period of warm water (10,11). With climate warming, northerly populations that now persist because of occasionally strong year classes in warmer summers will likely become ecologically more vigorous and productive with more regular reproduction. Also the limit of "struggling populations" should extend northward (11).

Numerous non-native marine or euryhaline fish species have colonized the Great Lakes due to unintended or deliberate introductions or direct invasions. On the whole there is a rough balance between the bad and the good effects of these non-native additions. Salmon introductions have balanced the sea lamprey invasions; the desirable and undesirable features of such species as smelt and alewife are comparable. In the Great Lakes Basin as a whole these non-native species will not likely be affected to the extent, say, of their extinction. The salmon may diminish in importance in the southerly part of the Great Lakes and expand in the northerly part. The harmful sea lamprey may flourish to a greater extent than heretofore in Lake Superior waters.

All the non-native species of some ecological and cultural importance in the Great Lakes have come from the East and West Coasts of America or from Europe. With climate warming there will likely be a gradual invasion of species that now have their northerly limits just to the south of the Great Lakes Basin (12). Table 1 shows a list of candidate invaders. None of these seems to pose either a major threat or a major promise as concerns contemporary human values related to the fish of the Great Lakes Region.

If especially important new introductions or invasions do occur as a direct or indirect consequence of climate warming, then they may well come from the coasts of North America or from the Eurasian continent. Such prospects have not yet been examined critically. Striped bass, of the same serranid family as the native white bass and the invading white perch, may well attract the renewed attention of those Great Lakes fishery experts who delight in "enriching" these ecosystems with new species.

The species associations of streams, with their

Table 1. List of fish species that will likely invade Great Lakes waters due to climate warming (12).

From the Lower Great Lakes to the Upper Great Lakes

grass pickerel
spotted gar
tonguetied minnow
river shiner
chain pickerel
river redhorse sucker
bigmouth shiner
bluespotted sunfish

From Mississippi and Atlantic Coastal Basins to the Great Lakes

shovelnose sturgeon
shortnose gar
goldeye
plains minnow
ironcolour shiner
Ozark minnow
blacktail shiner
steelcolour shiner
river carpsucker
blue sucker
golden topminnow
blackspotted topminnow
plains topminnow
mud sunfish
flier
banded pygmy sunfish
blackbanded sunfish
banded sunfish
bantam sunfish

representatives of taxa particularly valued by humans, may exhibit some of the more noteworthy changes due to climate warming. Small streams and lakes of the glacial moraines in the southern half of the Great Lakes Basin maintain valued cold-water associations, as with the prized native brook trout. With climate warming the groundwater aquifer (13) and the peak summer temperatures of streams will increase in such headwater areas. Brook trout populations will likely shrink and be extinguished in numerous marginal streams. The non-native brown and rainbow trout, also well-liked, are somewhat more tolerant than brook trout and will expand into those habitats which are not warmed excessively. Where waters become too warm for the trouts the streams will lose their attractiveness to contemporary anglers, since there is now no candidate small-stream species in the region that is even remotely as attractive to anglers as are these trout species. Maybe anglers will learn to value cyprinids, such as carp and creek chub, as is now the case in parts of Europe.

D. SOME EFFECTS ON WETLANDS FRINGING THE GREAT LAKES

Large wetlands still abut the Great Lakes, though many have been dredged out or filled in. Some have been severely degraded due to harmful human influences of many kinds (14), especially in the more densely settled, southerly parts of the Basin.

The areal extent of fringing wetlands in pristine lakes is roughly in direct proportion to the extent of vertical variation of a lakes' water levels, both within a year and between years as within a decade (15). Climate change may bring with it a change in the amplitude of such water level changes, either directly due to changes in "natural" evaporation and precipitation or secondarily due to "cultural" interventions. If the amplitude increases, then the areal extent of wetlands will increase and vice versa, assuming no offsetting cultural interventions. An ecological assessment depends on prior hydrological and cultural assessments.

The regime of water level fluctuations may not change, but the lake levels may do so, on average. If the rate of change is very gradual, then the wetlands would likely shift up or down slope, depending on whether the average lake level went up or down, with no major change in areal extent, when averaged over all a lake's wetlands. The local topography might be such that a relatively larger increase or decrease might occur in a local wetland.

As already indicated in preceeding sections, ecological productivity, per unit of habitat, would likely increase with climate warming in the absence of harmful human practices that have been entrained in some way by climate change. But this condition may be violated with many wetlands.

In the Great Lakes efforts are underway to remediate some of the worst abuses by humans on these lakes and their wetlands and streams, but the process is slow (16,17,18). Efforts at preserving healthy parts of the lakes, such as wetlands and streams, are slowly gaining in effectiveness. Climate change will bring additional changes through the primary natural chain and the secondary cultural chain of impacts. The cultural impacts may be severe, especially if relevant effects of climate change occur rapidly and human populations respond massively and rapidly with respect to urban, agricultural and industrial development. The more rapid such cultural responses will be, the more destructive they are likely to be to natural values, and especially those of the Great Lakes coastal zone.

E. CONCLUDING COMMENTS

Climate change may bring a massive influx of people into the Great Lakes Basin as the "water belt". It's earlier reputation as the "slum belt" and the "rust belt" have been countered by some regional ecological, economic and social rehabilitation (19,20). The climate warming will have acted to counter the Basin's reputation as a "snow belt". If the "sun belt" will have become the "drought belt", agriculture with its irrigation and run-off may again blossom in the Great Lakes Basin. Inter-regional shifts in human populations due in part to climate warming may bring with them a new wave of practices, related to agriculture, urbanization and resource industries, that are destructive of the Great Lakes aquatic ecosystems, especially in the highly-valued coastal zone (21). Such effects of climate change through the cultural chain may be more threatening to human values related to Great Lakes fish and wetlands than the direct effects due to increased temperature, changed precipitation and alterations in other climatic variables.

With respect to the more direct effects, the major consequences will relate to northward shifts of the limits and the centres of relative abundance of the valued species. None of the most valued species will likely be extinguished in the Great Lakes, though Lake Erie's Eastern Basin may become too warm to support a vigorous, rehabilitated lake trout population. It may be that Pacific salmon of Lake Michigan will not migrate into the southerly waters of Indiana and Illinois to the extent that they do now. These salmon species may become more abundant in Lake Michigan's northerly waters now under the jurisdiction of Indian tribes. Such changes would cause consternation to many anglers and their service industries, but those interests have recently accommodated themselves to even greater changes.

If we considered valued species as a class, then climate warming will lead, overall, to some increased productivity to the fishery (whether commercial, angler, artisanal or all combined). Some decreases will likely occur in many small headwater streams towards the south. Individually these streams have low ecological productivity, - the entire trout production of a small stream may not reach 10 kg per year. Where such a stream is managed for anglers who practice no-kill fishing, 10 kg per year is an appreciable "resource base" that provides many hours of prized recreation. Such streams may be the closest approximations to "sacred glades" that we have in the Great Lakes Basin, at least for such anglers. But newly revived urban and agricultural development likely would pose greater threats to such locales than would climate change acting directly on those ecosystems.

There appears to be little likelihood of a major direct impact on the fish of the Great Lakes by moderate climate warming, but moderate drying would be of greater concern. The fish of few if any locales will be unaffected, but the changes will be mostly in the nature of shifts in the relative abundance of species. There are candidate valued species that will flourish in waters in which present valued species will diminish, at least in lakes but perhaps not in southerly streams.

There may be massive indirect impact due to a new wave of urban and agricultural settlers whose impacts may not be well-controlled in a turbulent period of inter-regional accommodation of climate change. The streams, wetlands and near-shore waters would likely bear the brunt of such cultural impacts. Such waters have much greater ecological and cultural importance than the offshore waters of the lakes.

With respect to primary impacts through the natural chain of events, the Great Lakes may be naturally "buffered" to an extent greater than any other large freshwater ecosystem of North America. It may also be "buffered" culturally with respect to secondary impacts through humans in that strong inter-governmental programs now in place can be adapted to prevent or mitigate harmful new developments, if these do not occur under crisis conditions.

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FOREST MANAGEMENT STRATEGIES TO ADDRESS CLIMATE CHANGE

by

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Presented at the First North American Conference
on Preparing for Climate Change: A Cooperative Approach
Washington, DC
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INTRODUCTION

Climatic change of the magnitude and at the rates currently being forecast for the next 50 to 100 years would significantly, even drastically, affect forests (Harington, in press). Projected increases in global temperature, changes in precipitation, CO_2 enrichment and other atmospheric changes would shift existing climate-soil-vegetation equilibria, especially in mid and high latitudes. In Canada, where warmer tends to mean better, a first reaction is to welcome this change. In fact, while it may prove beneficial in the long run, perhaps the very long run, the adaptation could be painful. Trees being both stationary and long-lived, would be particularly vulnerable, as would wildlife whose habitats are specific forest ecosystems. The lack of an identified steady-state or end-point in this process has frightening implications.

Planning by predicting the future from past experience is a key to man's ability to cope with or manipulate his environment, especially in forest management where time frames are long. In the natural forest in most parts of North America, the trees are already growing which will provide wood or watershed protection for the next 50 to 100 years. Even in plantations of poplars and southern pines, stock selection and tree improvement have this time horizon. Foresters should be developing strategies for climate change now.

Frustratingly, uncertainty is so high that planning is an interesting intellectual exercise but can scarcely lead to any credible program. Although various scenarios agree generally on temperature increases, there is little consensus on changes in precipitation. The implications of "warmer-drier" as opposed to "warmer-wetter" are critical. To exaggerate, should Maine and New Brunswick introduce southern pines or Douglas fir? Until uncertainty is reduced, strategy development is limited to identification of concerns, prediction of ranges of possible reactions and speculation on which strategies might be required in various areas.

The following is a cursory exploration of these aspects, assuming that significant evolution of forests will occur within 50 years.

FOREST PROTECTION

If climate changes, the immediate role of forest management is to protect the forest resource we now possess. Fire, pests and abiotic diseases will all respond, sometimes to our advantage, sometimes not. The ability to control these destructive agents varies enormously.

Fire incidence would be affected immediately by weather and climate change, but adaptation of control programs would be relatively simple, although sometimes costly. Patrol aircraft, lightning detectors, precipitation radar, water bombers, mobile fire attack crews and command centre technology combine to make very flexible programs. In this time scale, adjusting regional programs could be readily accomplished as fire hazard and forest vulnerability evolved. Alpine and boreal spruce-fir forests would be especially vulnerable to decreased precipitation during the life of existing stands; hardwood and pine stands much less so.

Pest control strategies would be far more difficult to devise, partly because new pest complexes would be created, partly because pests would react to climate change more quickly than trees and forests.

Consider the scenario of a warmer and drier climate in the border zone of north-eastern U.S.A. and south-eastern Canada. Here, the spruce budworm is an epidemic defoliator of spruce-fir forests, especially where precipitation and consequently the balsam fir component are high, as in southern Quebec, Maine and the Maritime provinces. Budworm epidemics are stimulated by warm, dry weather (Martineau, 1984). Current control programs struggle to limit losses to endurable levels and might be unable to cope with more severe epidemics. Balsam fir occurs in cool, moist climates, so the long-term solution might be a natural replacement by spruce and jackpine, creating a less vulnerable forest, such as that now found in Ontario and Minnesota. For the existing forest, strategies could include massive salvage cutting such as that done in Cape Breton Island, improved technology for aerial spraying or accelerated research on new control agents such as a virulent budworm virus. Balsam fir stands in dry conditions would be highly vulnerable to fire, so controlled burning to speed species conversion or avoid catastrophic wildfire might be considered.

Concurrently, gypsy moth would probably assume more importance as a hardwood defoliator because it is now limited in part by cold winters. This increase might be reinforced in the long term if oaks, the preferred host species, replaced maple and birch. Gypsy moth control in more southerly regions has proven very expensive.

Conversely, the risk of hemlock looper epidemics in areas of maritime climate bordering the Gulf of St. Lawrence would decrease. The incidence of white pine blister rust (Lavallee, 1986) could well decline since infection and spread is favoured by cool, moist weather. White pine could be encouraged in place of balsam fir, but then white pine weevil would assume more importance.

Similar and far more detailed strategy considerations could be written for each climate change scenario in each region. The point to be retained is that existing pests could be maintained or even stimulated during climate change as long as the existing hosts endure, while new pests could well arise because of more favourable conditions. Even where climate change provided a management opportunity, the shift in strategy would entail costs. The magnitude of all of these costs is potentially enormous.

<u>Abiotic diseases</u> are perhaps the most discouraging aspect of climate change impacts on forests. As trees and stands became less and less adapted to the climate, stress reinforced by secondary diseases and insects would take an increasing toll. More frequent adverse weather events such as mid-winter thaws and mid-summer droughts would decrease vigour. General declines with typical dieback symptoms could be expected and may already play some part in those declines now experienced in Europe and North America.

Forest management strategies are difficult to devise because of the very large areas which could be involved, especially at maximum rates of change. Salvage harvesting could be envisaged, but sudden and massive oversupplies of wood are economically disruptive. Fertilization, drainage and strict control of secondary pests might be of some value on intensively managed sites.

FOREST PRODUCTION

Silvicultural treatments could facilitate adaptation of forests to changing climate. Strategies could be based on the predicted direction and rate of forest change, given the existing soil types and the anticipated change in climate. Evolution of species composition, changes in vigour and growth rates, and forest migration might be planned for, especially in planted and intensively managed forests. However, huge areas of North American and especially Canadian forests will continue to be managed only through harvesting strategies for the foreseeable future.

Natural regeneration and stand tending would use species selection as the basic tool for forest adaptation. Any given region contains a mix of species whose ranges cover a variety of temperature and moisture regimes. In any intervention, those species whose ecological amplitudes extended furthest in the direction of the anticipated change would be favoured. The need to maintain a vigorous forest might have to supercede commercial desirability of species. Rapid growth in the immediate future might have to be sacrificed to best survival at maturity. The most difficult regions to manage would be those with a limited number of species and extensive pure stands, such as the boreal forest. Where forest deterioration occurred at an appreciable rate, a general shift in species composition to pioneer species could be expected. Further, CO_2 enrichment might favour weed and broad-leaved species at the expense of conifers.

Tree improvement programs for plantations are selecting stock genetically improved for rapid growth with some attention to form and to disease resistance. Short rotations for planted trees undeniably provide management flexibility in the face of climatic change. It is ironic that the greatest change may occur where rotations are naturally longest. Consideration should be given to selecting stock having reasonably rapid growth over a broad range of ecological conditions, rather than maximum growth in specific sites or areas. Again, improvement programs for a given region should plan on the basis of anticipated climate change and existing soils. If significant northward displacement of selected stocks were planned, phenological reactions to day length should be considered.

Growth and yield predictions are essential tools in forest management which acquire a new degree of uncertainty in a rapidly changing climate. Allowable annual cut, returns on investment in management or, in the extreme case, perhaps even site selection for processing plants could be affected. Part of this uncertainty derives from the exposure of existing forests to changing climate. In a much longer term, it could involve a generally northern migration of ranges of tree species which, in Canada, could be into regions where soil factors would limit productivity for a very long time. The heavily glaciated Canadian Shield with generally thin, coarse-textured soils of low fertility interspersed with organic soils and exposed bedrock would not suddenly become highly productive just because the climate became more favourable to plant growth. Soil-forming processes would operate slowly.

If changes occurred at the maximum rates projected, it is at least conceivable that deliberate introduction of selected species and stock on specific sites destined for intensive management in advance of a forest migration would be advantageous.

For yield predictions, modelling of existing data for the extremes of climate and site within current ranges of species would provide first approximations.

HARVESTING

Planned cutting is one of the most powerful tools of forest management and, by favouring regeneration of selected species, could be used to accelerate change in species composition in directions imposed by climatic change. Harvesting operations themselves could well be affected by changes in length of the operating season, in access to fragile or wet sites or by impacts on road construction costs. However, as with fire control, the flexibility of the systems available for harvesting and the time scale involved would permit ready adaptation.

CONCLUSIONS

The ability to manage forests effectively is jeopardized by the prospect of rapid climatic change. In fact, until there is reasonable confidence in the direction and rate of change in precipitation as well as temperature, predicted reactions of forest vegetation and, therefore, development of management strategies will remain purely speculative.

Unfortunately, the need to plan is urgent even at minimal rates of change. If a reasonable level of confidence in climate prediction is attained, regional strategies can be developed providing relatively simple adaptations for activities such as fire and harvesting and far more risky, complex and costly ones concerning insects, disease, silvicultural treatments, tree improvement and growth and yield. Forest deterioration and migration present extreme difficulties.

Forest ecologists and forest managers think of weather as variable and climate as constant. In fact, this assumption is basic to all forest management planning at this time. If rapid climate change with no identified steady state is to occur, it is essential that we incorporate this radically different concept into our resource management philosophy. We may then be able to find opportunity in adversity.

Overall, the more rapid the rate of change of climate, the more costly and difficult will be the adaptation, whatever the eventual advantages or disadvantages. For forest management, energy and emission control policies (Mintzer, 1987) to delay change are imperative.

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STRATOSPHERIC OZONE MODIFICATION AND GROUND LEVEL OZONE

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ABSTRACT

This study was performed to determine the impact that potential changes in stratospheric ozone concentrations and surface temperatures might have on the chemical processes that create tropospheric ozone and cloud acidification precursors. The investigation consisted of two distinct parts. First, an assessment was performed of the ultraviolet radiation information and molecular absorption cross section and quantum yield data currently used in air quality simulation. This assessment addressed both the quality of existing data and approaches available for utilizing these data to determine chemical photolysis rates in the troposphere. Particular attention was paid to the photolysis reactions of ozone, formaldehyde, and acetaldehyde because these species absorb light in the spectral region where surface ultraviolet irradiance could increase due to decreased stratospheric absorption by ozone.

The algorithms and data resulting from this assessment were used in the second portion of the study to determine photolysis rates that might occur in the troposphere under future conditions of decreased stratospheric ozone. The sensitivity of photochemical dynamic processes was tested for a large number of urban airshed data sets under conditions of decreased stratospheric ozone and increased surface temperatures. The predicted surface ozone and hydrogen peroxide concentrations resulting from incremental changes in the assumed future stratospheric ozone and temperature parameters were analyzed for each city and for specific groups of cities. Instances of greater future oxidant forming potential were most common for cities with already high hydrocarbon control requirements. The increased energy input during future scenarios provided more rapid ozone formation in all cases, indicating the possible exposure of a larger portion of the urban population to higher ozone concentrations nearer to the center of the urban plume.

INTRODUCTION

In recent years scientists have become increasingly aware that potential chemical modification of the upper atmosphere by trace gases may produce an overall global warming by blocking the escape of thermal infrared radiation. This phenomenon is commonly referred to as the "Greenhouse Effect." In addition, the chemical reactions of halocarbons, methane, and N_20, may cause future decreases in stratospheric ozone levels.[2] One consequence of this decrease would be an increase in the penetration of ultraviolet radiation to the troposphere, since stratospheric ozone is a principal attenuator of radiation in the middle ultraviolet radiation spectral region. A higher intensity of ultraviolet radiation at the earth's surface, combined with higher global temperatures, might increase the prevalence and intensity of photochemical smog episodes in populated areas and result in an unanticipated deleterious impact on public health.

An increase in the prevalence of photochemical smog might result because a greater transmission of ultraviolet radiation would augment the principal energy source responsible for photochemical reactions in the troposphere. Combined with higher global surface temperatures, this could lead to an increase in the reaction rates of a number of photochemical reactions critical to smog formation. These potential increases in specific photochemical reactions rates have been largely ignored in studies of future chemical changes within the planetary boundary layer. Any enhanced photochemical reactivity could increase the prevalence and magnitude of regional and urban ozone formation, and augment both the rural and urban contributions of acid precursors by increasing the production capacity for oxidized species. It was our intent in this study to address the magnitude and chemical dynamics of such impacts.

Because the rates of photolysis for certain chemical species may vary strongly with increased ultraviolet transmission, the first part of the study assessed the uncertainty associated with the calculation of the tropospheric photolysis rates of specific chemical species. We addressed both the uncertainty in fundamental chemical parameters and the error associated with determining surface actinic flux under present and future conditions. This was followed by an analysis of the possible impacts of increased surface temperature and decreased stratospheric ozone (and thus, increased near-surface photolysis rates) on the photochemistry of various airsheds. Because the effects of projected global changes of near-surface photochemistry will vary with the characteristics of each airshed tested, we chose to analyze a large number of different test sets so that a reasonable variation in input data could be applied. Large numbers of data sets are currently available only for urban areas whose compliance with the air quality standards for ozone must be verified. Atmospheric oxidant formation in urban areas is one of the most studied atmospheric photochemical phenomena because of the potential health effects of high ozone concentrations in areas of high population. For this reason, these systems are also probably the best understood, and because of high amounts of anthropogenic emissions of oxidant precursors, could be the most immediately sensitive to potential global changes. Thus, we chose to investigate the impacts of potential global changes on this type of system first.

PROCEDURE

Range of Future Values

In such a sensitivity study, it is also necessary to formulate some understanding of the possible ranges of projected surface temperature and stratospheric ozone changes anticipated. Our methodology was to analyze available information and then devise two sets of values, representing moderate and extreme future conditions. The moderate values were selected to be between projections for the period 2010 to 2030, and the extreme values represent even higher but possible conditions, especially for decades later in the next century. From these assumptions we formulated a set of future scenario temperature and ultraviolet light (photolysis rate) conditions. It is beyond the scope of this discussion to consider the complex perturbations that may alter future surface temperatures. However, recent efforts in global climate modeling indicate that global warming could increase the average temperature by as much as 1 to 3 K by the year 2030. Therefore, in the scenarios considered in this work, we used surface temperature increments of 2 and 5 K over the measured temperature profiles for each data set.

The potential changes to mid-latitude ozone column density must be estimated before attempting to calculate representative photolysis rates. We chose a base-case ozone column of 0.300 cm-atm for all simulations. This represents approximately the monthly average at North American latitudes for the July and August period when most measurements in the test data sets were performed. Daily meteorological conditions specific to each data set are assumed to be contained in the simulation of each base-case data set. As we will discuss later, only base-case simulations that accurately predicted the actual measurements for a specific day were further utilized for future scenario sensitivity testing. Such a procedure acts as a filter to eliminate days with conditions unlike the assumed (monthly average) base-case conditions. In this way, we attempted to focus on future photochemical changes that were due to the increases in temperature and decreases in ozone column relative to the base-case values. The moderate and extreme overhead ozone column conditions chosen in this study were 0.25 and 0.20 cm-atm, representing 16.7 and 33.3 percent decreases in ozone for the future test period. These conditions represent current chemical modeling estimates (15 percent decrease predicted by the middle of the next century) and Nimbus 7 satellite data (possible decreases of about 0.5 percent/year).

The most direct way that depletion of stratospheric ozone could induce greater photochemical reactivity in the lower troposphere would be through an alteration in the magnitude of the ultraviolet irradiance at the earth's surface. This variation must be accounted for prior to simulation, and hence, we briefly consider the ozone absorption process and the uncertainties in the calculation of tropospheric photolysis rates.

Below 300 nm, the ability of ozone to absorb radiation increases dramatically into the Hartley bands (200 to 300 nm), resulting in the cutoff of short wavelength ultraviolet transmission to the earth's surface. However, in the spectral region between 300 to 350 nm (the bands of Huggins) the ability of ozone to absorb light decreases with increasing wavelength, allow some transmission of ultraviolet radiation to the earth's surface. Hence, the spectral region, in which an increase in ultraviolet irradiance due to diminished stratospheric ozone absorption should be manifest, will probably be confined to a rather small range between 310 and 280 nm because the change depends completely on the absorption characteristics of ozone, which is a much poorer absorber of radiation above 310 nm. A number of key tropospheric trace species photolyze to very reactive products upon absorption of radiation from this spectral region where ultraviolet irradiance is expected to increase. Therefore, even a relatively small change in total available radiant energy may induce a relatively large increase in certain tropospheric photolysis rates.

Photolysis of stable molecules is the major source of new radicals in tropospheric gas-phase chemistry. In atmospheres capable of sustaining even a moderate rate of photochemical reactivity, a greater production rate for new radicals would tend to increase the initial and continued oxidation of organic compounds, resulting in additional thermochemical radical generation and sustained production of additional stable species capable of more photolysis. Therefore, the increased radical mass flux that would result from potential enhancement of some photolysis reactions could translate into more reactive tropospheric photochemistry. The result could be increased production of those oxidized species now regulated as photochemical oxidants (urban ozone), or of other compounds (peroxides) critical to the formation of acidic precipitation after transport out of an urban area.

Because our goal was simulation of present and future urban atmospheric systems, we felt it was necessary to estimate the values and uncertainty for these rates as they changed with decreasing ozone column densities. We mainly focused on the uncertainty associated with the calculation of surface photolysis rates for ozone [to $O(^1D)$] and formaldehyde, since these are the most significant, radical-generating photolysis reactions in the spectral region of interest and in the urban atmosphere in general. Thus, their associated uncertainty translates almost directly into uncertainty concerning the radical production rate of polluted air masses. We also identified data and algorithms we felt to be potentially useful in the development of a new generation of ultraviolet actinic flux calculation schemes for current and developing models. Our predictions were then compared with actual measurements, and the uncertainty associated with each step of the process was examined. Because the calculation of atmospheric photolysis rates is the product of actinic flux and specific molecular properties integrated over wavelength, we addressed three separate areas: (1) the methods and data needed to calculate actinic flux, (2) uncertainties in experimentally derived values for molecular properties, and (3) the integration approach and related uncertainties. We discuss the results in the next section.

Simulation Protocol

The goal of the atmospheric simulation phase of the study was to investigate the potential changes in urban oxidant formation caused by possible future alterations in global climate. More specifically, we were interested in (1) additional photochemical reactivity and (2) the amount of oxidant formation that could occur as a result of future increases in surface temperature and decreases in stratospheric ozone (increases in surface ultraviolet irradiance and photolysis rates). Three different ozone column densities and temperature ranges were used in the future scenario calculations. In addition to 57 single-day city scenarios, we studied multi-day impacts for two cities--one that had attained the National Ambient Air Quality Standard (NAAQS) for ozone, and one in non-attainment status. A second photochemical kinetics mechanism was used in one set of simulations to verify that the results were not mechanism-specific. Also, we felt it appropriate to use the OZIPM photochemical trajectory model in our investigation of future urban impacts since, when combined with the EKMA procedure, this model is most often employed to determine the amount of NMOC reduction needed to achieve compliance with the ozone NAAQS of 0.12 ppm. As we will see, EKMA calculations can also aid in providing estimates of atmospheric and emission conditions expected in future scenarios.

In this study, we felt that a protocol which merely employed the resimulation of a present-day scenario using different photolysis rates or temperature values would not provide a sufficiently reasonable estimate of anticipated future urban conditions because mandated control requirements must necessarily alter present conditions. Since the EKMA procedure is often used to determine the amount of NMOC reduction that will ideally be implemented in the future, we utilized this direct link with the regulatory process to determine more realistic future scenarios. Therefore, all present-day base-case data sets were implemented in OZIPM-3. For those with reasonable fits to the observed data, standard EKMA calculations were performed to formulate scenarios of future attainment in each city based on the alleviation of current smog scenarios. We felt that this approach would provide a much better estimate of future base-case scenarios with which to assess unanticipated (in the EKMA) perturbations due to changes in the two variables (temperature and ultraviolet radiation) of interest in this study. Of course, this protocol assumes "ideal" performance in the EKMA calculation method and an "ideal" response of an urban atmosphere to EKMA-derived emission controls. As noted, we imposed the constraint that the simulated ozone value and the design (measured) concentration should not vary excessively. In this way, the EKMA program is not required to compensate for a poor fit, but only to calculate the ratio of NMOC reduction needed to "ideally" produce 0.12 ppm ozone. As noted above, this procedure also gives some indication that reasonable replication of daily meteorological and ozone column conditions occurred, so that the future sensitivity tests could focus on the impacts of changes relative to the base case conditions.

Our initial, single-day modeling data set consisted of atmospheric measurements from 45 days in 10 cities. There were actually 57 initial base-case simulations because some days were modeled with a multiple number of trajectories. Individual, NMOC, NO_x, and design O_3 values, elevation, location, regional albedo, temperature, and mixing height profiles, were used for each city. The number of overall test sets was reduced to 15 by testing of the goodness-of-fit between measured and simulated hourly maximum ozone concentrations for present base-case simulations. EKMA calculations were then performed to determine the "ideal" NAAQS compliance conditions for each base-case data set. From the EKMA results, a future base-case data set (still with normal temperature and ozone column conditions) was derived and simulated to verify that those conditions produced ozone at the level of the NAAQS. Then, using this future base case as the "ideal" anticipated result of prescribed NMOC reductions, we were able to estimate the extent of unanticipated (by the EKMA) impacts resulting from the photochemical changes caused by increased temperature and ultraviolet irradiance. This was done by the incremental increase of these values and the analysis of resulting changes in the concentrations of ozone and other chemical species.

Since the city-specific data sets span a wide range of urban oxidant production capacities, we consolidated our analysis and the following discussion by creating three general group classifications:

Group 1: High ozone NAAQS exceedence days. In this group we include all days with design values greater than 0.17 ppm. There are ten such days in the 45 days simulated. These data sets are from Los Angeles, Chicago, New York, Boston, Philadelphia, and Washington, representing oxidant production episodes in regions where severe ozone exceedences are common.

Group 2: Less extreme nonattainment days, often representing cities that require moderate control (30 to 50 percent) of organic precursors to achieve the ozone NAAQS. Hourly maximum ozone concentrations are between 0.17 and 0.14 ppm in this group. Local meteorological conditions can influence the magnitude of the ozone production in many of these cases.

Group 3: Days that are nearly in compliance with the NAAQS for ozone. These data sets provide future sensitivity tests with current ozone production at 0.13 ppm or below. These data are scattered among a few test cities, including Boston, Nashville, and Tulsa.

We have used these groupings because common group characteristics facilitate later discussion of chemical dynamics. Although these data could be considered typical of each individual city's ozone formation profile, we will usually name specific cities only to identify the source of input data for an example data set. One notable exception in the following discussion concerns the two data sets chosen from the Seattle data. As with many data sets collected for use in the 1982 SIP process in smaller cities, some measurements needed for OZIPM input parameters appear to be rather uncertain. In this case, we refer to both the precursor concentrations (which appear to be rather high) and the morning mixing height (which may have been less than the 250-m values used in the SIP calculations). The calculated results for those days do not easily fit into any of the grouping schemes. However, their results do demonstrate some important atmospheric processes; so, although they are uncertain, we discuss the conditions and predictions from those two tests to demonstrate certain aspects of chemical dynamics. Therefore, our discussion focuses on the three general groups, and a fourth test based on the Seattle data (denoted as Group 4 in the following discussion). We feel that this grouping scheme is as specific as the current data will allow. We stress that though it is based on data from one city, even the Seattle data should be considered a general test case since a much larger and better defined set of city-specific measurements must be considered before the unique characteristics of any individual city can actually be discussed.

RESULTS AND DISCUSSION

Assessment of Photolytic Rate Calculations

We initially analyzed the methods and data needed to calculate actinic flux at the earth's surface. The nature of such calculations is complicated because the determination of actinic flux for differing conditions and location requires consideration of a wide range of complex atmospheric interactions. Rigorous attempts were made a decade ago, resulting in the creation of a number of actinic flux data sets for various conditions. These data sets have been used extensively over the last decade in almost all photochemical modeling studies of tropospheric air masses. We believe that an update of this work is now in order, if for no other reason than to include more recent extraterrestrial flux and atmospheric aerosol data in these calculations and to provide actinic flux results for conditions not addressed in the original work (e.g., variable ozone column densities), but now becoming more important. These new calculations must also be carried out at smaller integration intervals to provide flux data resolved to a magnitude comparable with that of molecular data, so that mathematical averaging errors in the photolysis rate calculations can be limited. This new data would also be very useful in improving the mathematical formulations used to estimate actinic fluxes for conditions not directly included in the data.

Our analysis of fundamental molecular data focused on the short wavelength photolysis reactions of ozone and formaldehyde. The greatest individual area of uncertainty in those reactions is found in the absorption cross-section formaldehyde data. The two key studies in this area obtained results that differed by about 30 percent. Since formaldehyde is a very important photolytic species in the troposphere, these numbers translate into a large uncertainty in the radical production capacity of organic oxidation products. We believe that this discrepancy should be alleviated, either through reevaluation of existing data sets or through additional experimental work to develop more data. Absorption cross-section and quantum yield data for ozone are less uncertain, primarily because they have been the objects of experimental investigation for a longer period of time. A somewhat larger associated error develops for ozone photolysis to form $O(^1D)$, however, because this process occurs at the surface ultraviolet cutoff, where actinic flux calculations are less certain. An experimental program designed to measure surface flux distributions in the middle ultraviolet range (particularly in the region near the solar cutoff) would provide information with which the error of j_{O1D} calculations might be diminished and could also yield important data for evaluating and improving actinic flux calculation schemes.

We also investigated the methodology involved in calculating photolysis rates. In cases where two or more the product terms (actinic flux, quantum yield, and absorption cross section) were highly wavelength-resolved, errors resulted if the wavelength intervals used in numerical integration were much larger than the significant resolved features in the individual functions. This averaging error was only on the order of ten percent, but could be easily eliminated if calculations were performed at 1 or 2 nm intervals. Again, this finding points to the need for a new set of more highly resolved actinic flux calculations.

Evaluation of the Impact of Global Changes on Tropospheric Photochemistry

This phase of the report focused on simulating the photochemistry of urban air parcels and evaluating the effects of potential changes in ozone column density and surface temperature. The modelling protocol and input data sets were discussed above. For discussion purposes, the 15 single-day test cases were grouped into four general categories also discussed earlier.

Of primary importance to the impact that future temperature increases or ozone column decreases might have on the photochemical dynamics of an urban system is the method by which the additional energy associated with those changes is input into that system. Increased surface ultraviolet irradiation caused by a diminished ozone absorption capacity in the stratosphere follows a diurnal curve dependent on the elevation of the sun. On the other hand, energy input to the earth's surface through Greenhouse warming takes a less direct route. Regarding impacts on ozone concentrations and other oxidized species, two distinct types of effects can be seen in the future scenarios; these effects can be linked to the differences in energy input dynamics. Because global surface temperature increases were simulated by the addition of 2 and 5 K to the original, city-specific temperature profiles evenly across the day, the effects of the temperature increases were slight increases in reaction rates and somewhat greater formation of ozone and oxidized products across the entire simulation period. This is to be expected since most temperature-dependent reaction rates increase with increasing temperature. The second type of impact, resulting from the enhanced (due to depleted stratospheric ozone) ultraviolet irradiation function, was an increase in the rate of photochemical reactivity centered around midday.

In all test cases studied, an increase in photolysis rates due to decreased stratospheric ozone caused a more rapid formation rate for ozone and other oxidized products. Because most additional energy input was concentrated in an already photochemically reactive period of the day, the impact was often more dramatic than that of the temperature change. Levels of ozone at or near the NAAQS (0.12 ppm) were achieved much earlier, sometimes hours earlier, at the time when an air parcel might be over more populated areas earlier in the trajectory. This would occur because the midday enhancement of photolysis rates provides a greater radical production rate and radical concentrations, thereby increasing short-term reactivity so that these photochemical systems can convert precursors to oxidant more efficiently. However, this enhanced reactivity may not always result in greater maximum ozone concentrations because that measure of oxidant-forming potential is also a function of available precursors and meteorological conditions. Hence, while increased ultraviolet irradiance from depleted stratospheric ozone is predicted to increase short-term reactivity in an urban air parcel, these conditions will not always result in greater maximum concentrations because such long-term measures are more a function of the specific system. Air parcels with low precursor emissions and beneficial meteorological conditions may actually produce lower maximum concentrations of oxidized products because the enhanced reactivity may consume a large fraction of the precursor species under conditions earlier in the day that are less favorable for oxidant formation.

For the general group of scenarios just described, our simulations predict increases in maximum hourly ozone (over the 0.12 ppm of the future based scenarios) at about 1.4 ± 0.5 percent per degree Kelvin increase for the first three groups, with the Group 1 cities at the more reactive extreme. With respect to changes in ozone column density, we predicted a 1.1 percent increase in maximum hourly ozone concentration for each percent decrease in ozone column for the Group 1 cities, while the rates of increase for the Groups 2 and 3 cities were very near zero. Some of this variability was seen as an artifact of the EKMA calculation procedure, since the EKMA procedure terminates its calculations at 1800 hours. In this way, additional oxidant-forming potential, which is only realized after 1800 hours, cannot be accounted for. For the Group 1 EKMA attainment and future base-case simulations, 0.12 ppm of ozone was formed at 1800 hours, but there was an increasing slope at that time, indicating additional oxidant-forming potential. Future conditions of enhanced ultraviolet irradiance utilized this potential more efficiently to produce higher levels of ozone prior to 1800 hours. Therefore, those test cases (Group 1) showed more extreme sensitivity to future changes in ozone column densities.

We recognize that simulations in which some of the rates in the chemical mechanism vary between present and future scenarios was never an intended application of the EKMA. On the other hand, when it is possible to account for a large fraction of the oxidant-forming potential, as in the base-case simulations for Groups 2 and 3 where the ozone maximum concentration occurred prior to 1800 hours, very little additional ozone formation was predicted with changes in future parameters because a large fraction of the oxidant-forming potential was already accounted for. Using our estimates of moderate (+2 K and -16.67 percent ozone column density) and extreme (+5 K and -33.3 percent ozone column density) conditions, we predicted group-average ozone concentrations of 0.132 and 0.120 ppm for Groups 2 and 3 at the extreme conditions. Hence, though ozone forms more rapidly in these future scenarios, the concentrations do not significantly exceed the NAAQS for even the most extreme conditions tested. Conversely, for Groups 1 and 4 average concentration results were 0.148 and 0.150 ppm for moderate conditions and 0.174 and 0.207 ppm for extreme tests. Because of the rather significant changes predicted for the Group 1 and 4 test cases, we also analyzed the data for an indication of whether synergistic interaction between the two perturbations would occur. We found that, for the cases available, the combined effects of coincident increases in both parameters were sometimes additive, but not synergistic. Such a finding is consistent with our description of the urban photochemical processes, assuming that there is a limit to the oxidant-forming potential of an air mass.

The formation of other oxidized products such as nitric acid and hydrogen peroxide was found to be specifically dependent on the types of processes by which they form in an urban atmosphere. For instance, the formation rate and eventual yield of nitric acid is related to the hydroxyl radical concentration and the amount of NO_x available.

These two parameters are closely linked to ozone concentration, since NO_x is an ozone precursor and ozone photolysis is the key source of hydroxyl radicals in these systems. Hence, the impacts of potential global changes on nitric acid formation parallel those of ozone and are limited by available NO_x. On the other hand, hydrogen peroxide is formed by the combination of hydroperoxy radicals, which only accumulate after NO_x is depleted. An increase in photochemical reactivity will deplete NO_x faster and allow hydroperoxy radical (and therefore, hydrogen peroxide) to form for longer periods and at higher concentrations. In this study, the predicted future increases in photochemical reactivity stem mainly from projected future decreases in ozone column density; thus, hydrogen peroxide was found to be very sensitive to this parameter.

We have also found that NMOC emission control designed to attain the NAAQS for ozone appears to be a very effective hydrogen peroxide control since one net effect of NMOC control is to reduce the reactivity of a system and thereby reduce the consumption rate of NO_x. Since the hydroperoxy radical concentrations are highly sensitive to NO_x concentration, the additional remaining NO_x holds down the hydrogen peroxide formation rate. Conversely, as projected conditions of future global change were implemented in our test cases, NO_x was again depleted more rapidly and hydrogen peroxide concentrations began to increase significantly. For our moderate test conditions, control of NMOC to attain the ozone NAAQS was predicted to also limit hydrogen peroxide to about 70 to 80 percent of its original base-case concentration. However, as ozone column conditions were changed to the extreme case, more hydrogen peroxide was formed than in the original base case, even with the added NMOC control.

CONCLUSIONS AND RECOMMENDATIONS

We believe that the current actinic flux, absorption cross section, and quantum yield data sets result in calculations of ozone [to form $O(^1D)$] and formaldehyde photolysis rates within an uncertainty of about 50 percent. These are the most important photolysis rates in the simulation of tropospheric photochemistry, and more confidence in model results would be gained if this uncertainty could be limited to more acceptable bounds. We feel future efforts to limit this uncertainty would provide additional confidence in all air quality simulation. These efforts should (1) use currently existing information to develop improved actinic flux data sets and computer formulations, and (2) make additional experimental measurements, particularly of formaldehyde absorption cross sections, short wavelength actinic flux distributions, and actinometrically determined j-values, to provide critical information in the most uncertain areas.

Our simulations of urban photochemical systems indicate that some areas, predominantly those rich in emissions of oxidant precursor species, exhibit strong tendencies to be more reactive given additional energy input from increased temperatures and increased ultraviolet irradiation. This added reactivity was evident from both higher concentrations of oxidants and radical species and more rapid formation of these species. We have established some limits to the extremes of change that could occur in urban scenarios and suggest that continuation of such an effort should focus on four aspects: (1) use of the newest and more extensive 1987 SIP data along with the recently developed Carbon-Bond Mechanism-IV/OZIPM-4 model to obtain more specific information related to the extent of the impacts found in this study; (2) use of such models and data to study parameters not varied in this study, but now predicted by GCMs to be variable (including water vapor, mixing height and cloud cover); (3) use of regional models such as the ROM or RTM-III, to analyze linked, multiple, urban trajectories in a unified regional domain; and (4) use of a more complex gridded urban model, such as the Urban Airshed Model, in conjunction with demographic data to evaluate the exposure-related impacts of reactivity changes predicted to occur with smaller ozone column densities.

POTENTIAL EFFECTS OF CLIMATE CHANGE AND OZONE DEPLETION ON AIR QUALITY

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Programs for attaining and maintaining the national ambient air quality standards established under the Clean Air Act are well established in state and local governments and the regulated community. Substantial progress has been made in meeting many of the standards, but continued efforts are needed for most; in addition, substantial concern exists over the question of developing programs for acid deposition. Little attention has been paid by the "traditional" air quality management community to the implications of stratospheric ozone depletion and global climate change for affecting troposheric air quality. This is due, in varying degrees, to lack of hard information on the subject, a belief that changes are unlikely to occur in the normal planning horizon, and the perception that air quality changes are a relatively minor concern when compared to the other projected effects of global ozone depletion and climate change. Nevertheless, it is becoming apparent that some measure of global effects appear inevitable in the next 15 to 30 years. Preliminary indications from present assessments suggest that these and future changes may have major implications from an air quality management perspectives. It is therefore important to examine these implications and to conduct more detailed investigations on the more important areas of concern.

Information presented at this conference (Whitten, 1987; Hansen, 1987) suggest that global effects on troposheric air quality can be summarized as occurring through three major mechanisms: 1) Increased penetration of UVB; 2) the general warming trend; and 3) as yet unspecified changes in meteorological patterns on regional scales. Some of the potential effects on air quality of each of these changes are summarized below.

Increased UVB

In addition to the more widely discussed effects of the increased ultraviolet radiation associated with stratospheric ozone depletion (skin cancer, effects on biota), the increase in UVB can also have substantial effects on tropospheric air quality. As shown by Whitten (1987), the increased radiation increases the photolysis of both volatile organic chemicals and ozone. The net effect would be to speed up the smog formation process, resulting in peak ozone levels occurring earlier in the day and, in general, at higher concentration. The preliminary local scale modeling by Whitten suggests a 10 to 25% increase in peak ozone concentrations are possible for moderate reductions in stratospheric ozone (17% decline in Dobson number). Paradoxically, one simulation beginning with very high ozone levels indicated that increased UVB could decrease peak values. Another air quality related effect of stratospheric ozone depletion is the more rapid formation of hydrogen peroxide, which would increase the rate and extent of oxidation of sulfur and nitrogen oxides. This would increase levels of acid aerosols, perhaps decrease local deposition of acidic gases, but increase potential deposition in precipitation.

General Warming

The general increase in global temperatures predicted over the next several decades will have direct effects on air tropospheric air quality. Higher temperatures result in increased peak ozone levels, and the effect appears to be additive to that of increased UVB. In this case, the increase in ozone concentration comes with a reduction in the levels of another smog component, PAN (Whitten, 1987). The increase in global temperatures will be manifested in larger numbers of hot days (Schneider, 1987) that are more conducive to ozone formation. Thus, both the number of exceedances of ambient standards and the peak concentrations will increase with temperature. The higher ozone concentration represents an added health stress to individuals already stressed by the increased heat.

Other effects of warmer temperatures can increase or decrease emissions of common air pollutants in the troposphere. Higher temperatures will produce greater evaporative emissions of volatile organic chemicals. The increased consumption of electricity for cooling could increase emissions of nitrogen and sulfur oxides from generating stations. This increase in the warmer months would be in some measure offset by the decrease need for heating. Emissions of particulate matter from wood stoves would also decrease.

Meterological Patterns

Current air quality planning and modeling is based on the historically determined record of meteorology. Changes in the fundamental patterns of transport, temperature, precipitation, stagnation, and the like that accompany global change could have major implications for control programs. Because the current predictive capability for regional effects is quite limit, we can only speculate about the potential effects. For example, more stagnation would bring increased pollution levels, while a change in circulation patterns on the east coast could ameliorate the effects of otherwise increased temperatures. Increased cloudiness and precipitation would serve to reduce particles and ozone pollution, while dryer conditions would increase fugitive particle loadings.

Conclusions

It is clear that the preliminary assessments of the effects of predicted climate and stratospheric ozone changes on tropospheric air quality indicate potential responses of substantial concern to the air quality management community. From this perspective, the key areas needing immediate attention are assessments directed at improving our understanding of changes that may occur over the 10 to 30 year planning horizon. The likely effects of increased UV and warming are amenable to more detailed assessments with current analytical tools. Nevertheless, developing improved capabilities in these areas is quite important. Substantial improvements appear needed in modeling capability before reliable assessments of regional meteorological effects on air quality are possible.

GLOBAL WARMING, STRATOSPHERIC MODIFICATION AND AIR QUALITY: EFFECTS ON THE NATURAL ENVIRONMENT

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I. INTRODUCTION

In addition to any difficulties which human beings or natural resources may experience in adjusting to the direct consequences of climate change and ozone depletion, the intensification of existing air quality problems is an important indirect consequence. Ozone depletion will increase ultraviolet flux to the surface. Ultraviolet flux increases and climate changes, in conjunction with increasing SO_2, and NO_x, and hydrocarbon emissions, enhance ground level oxidant and acid levels. Acid deposition and oxidants cause forest and watershed degradation. In this article we briefly discuss these consequences, the most significant of which result from the creation of an oxidant-rich troposphere. We discuss these problems in greater detail elsewhere.[1]

II. TROPOSPHERIC OXIDANTS

The depletion of ozone in the stratosphere, a warmer climate, and increases in anthropogenic gases such as methane, non-methane hydrocarbons (NMHC) and NO_x in the troposphere all have implications for tropospheric concentrations of oxidants, such as ozone and hydrogen peroxide. The ecological consequences of enhanced oxidant concentrations arise from their phytotoxic properties.[2] Oxidants such as ozone and hydrogen peroxide can form in the presence of UV-B in both atmosphere and surface waters, and react rapidly in chemical and biological systems. Oxidant concentrations may increase due to increasing emissions of NO_x and hydrocarbons, due to increased UV-B, and higher temperatures. The photochemistry is discussed elsewhere.[3]

Simulations of future urban[4] and rural[5] ozone and hydrogen peroxide concentrations have been reported. From these studies and from simulations of the current atmosphere, we can place bounds on ozone concentrations for a world which is 3K warmer, has a substantial UV-B enhancement (~15%), and has pollutant emissions increases as in Table 1. Taking together the NO_x changes projected for the year 2030, with an equivalent NMHC change, we project an increase in rural ozone levels of nearly a factor of two in the U.S. In Western Europe, projected air emission controls may limit oxidant increases. However, in Eastern Europe and in industrial regions in developing countries, emissions growth can be expected to lead to ozone increases in excess of those in the U.S., absent stringent abatement measures.

Model simulations[4] suggest that hydrogen peroxide concentrations (H_2O_2) are more sensitive than ozone to the combined consequences of increased temperature, UV-B, NO_x, and hydrocarbons. Concentrations of this pervasive, highly soluble phytotoxin, currently measured in high concentrations in the gaseous atmosphere, in fog and precipitation, and in surface waters, can be expected to increase markedly in the future in rural areas. In section III, we explore the consequences of enhanced oxidants for natural ecosystems.

Airborne oxidants, related acidic aerosol and other smog components are also associated with respiratory and cardiovascular problems in humans. In polluted urban areas, such difficulties will also be exacerbated by the higher temperatures associated with climate change. Smog-related mortality and morbidity rates may be expected to increase.

III. CLIMATE CHANGE AND TEMPERATE FORESTS

The relationship of the atmosphere to the forest is determined by its impact on trees, other vegetation, surface and groundwater, soils microbes, and even animals. These interactions are so varied and complex that it is difficult to be definitive about the effect of atmospheric changes.[6,7] In general, increasing temperature and perhaps increasing carbon dioxide concentration will increase primary productivity.[8,9] However, forests will come under stress as their appropriate climate zones shift due to temperature and moisture changes. Temperate forests are already under stress from air pollution in both North America and Europe.[10,11,12] A variety of symptoms of this stress are currently observed. How these forests react to an additional climate stress is a complex matter. Some insight can be gained by examining current forest degradation mechanisms.

Mechanisms for Anthropogenic Forest Change:

Five biogeochemical mechanisms which have been proposed as contributors to forest damage are--

a. gaseous pollutant interaction with foliage;
b. acid precipitation or acid fog water surface interaction with foliage;
c. acid deposition mobilization of metals in soils and subsequent biotic-uptake, and associated soil nutrient impoverishment;
d. toxification of soils by atmospheric deposition of metals; and
e. nitrogen "overfertilization."

Visible effects include fine root damage, yellowing of conifer needles, and crown dieback. Ozone as well as sulfur and nitrogen oxides are known to be phytotoxic and may produce such visible symptoms at least at the higher end of the ambient concentration spectrum. Very acidic rain may visibly damage foliage.[13] In addition, both ozone and sulfur dioxide inhibit photosynthesis in absence of short-term visible damage,[14,15] which may explain the broad growth reductions inferred from tree ring data.[16] The other mechanisms are increasingly speculative. Let us examine the first three mechanisms in detail.

Gaseous pollutants are phytotoxic at levels observed near urban areas.[13] Controlled experiments indicate that ozone, sulfur dioxide, and nitrogen oxides in combination are capable of causing visible damage to conifers.[13,17] It is uncertain as to whether any one of these pollutants alone is capable of damaging trees at levels observed in rural areas, but combinations of these gases at low levels may act synergistically to damage trees.

As a result of anticipated atmospheric changes (Table 1), damage from gaseous pollutants could increase substantially, and the result may be non-additive should SO_2, O_3, and NO_x increase simultaneously. In particular, the vulnerability of vegetation to climate extremes may be enhanced by high pollutant concentrations.[15]

Also of concern is the potential for damage from H_2O_2. The phytotoxic properties of this chemical in droplets has been reported,[18] and its high solubility suggests that it may be easily absorbed by foliage. H_2O_2 is pervasive in atmospheric droplets and its gaseous abundance may increase several fold if temperature, UV-B and atmospheric gases increase (see Section II).

Acid precipitation or acid fog may affect foliage, either synergistically with O_3 (or H_2O_2) or separately by leaching nutrients and destroying the protective coating on conifer needles.[13,18] Higher temperatures and UV-B changes can affect this mechanism in two ways. First, atmospheric droplets and droplets on foliage are photochemical "factories" due to internal reactions. Temperature and UV-B increases will enhance droplet acidity by increasing photochemical activity inside and outside these droplets (followed by absorption). In addition, changes in precipitation frequency will alter the surface concentration of dry deposited acids on foliage. Where dry intervals lengthen, the acid stress to leaves will increase. However, drier conditions may also result in lower surface mobilization of pollutants.

In some areas, the effect of acid deposition on soil chemistry will lead to increases in metal mobility in soil solution. Where soils are already acidic and where climate change also reduces runoff, vegetation will absorb less water with lower pH and higher metal concentrations. Long-term soil nutrient impoverishment may slow where runoff decreases. However, increases in SO_2 or NO_x emissions coincident with runoff decreases could increase both nutrient loss and metal concentrations. Soil impoverishment due to acidification has already been noted in Europe, but only the most sensitive soils are seriously affected on decadal timescales.[19]

Temperature increases due to climate change can also enhance soil water acidification.[20] High soil temperatures lead to rapid mineralization of humus. Nitrate deposition of as much as 100 kg/hectare already competes as a source with internally cycled nitrogen in some temperate forests. Increasing temperatures and nitrate deposition will lead to acidic discharge of nitrates into soil solution. The associated metal mobilization may damage vegetation. Sporadic soil water acidification during warm episodes may trigger region-wide forest decline in combination with pre-existing stresses. A synergism between acid deposition and climate results because vegetation absorbs a progressively small fraction of available nitrogen as deposition increases. Most important, the increasing occurrence of excessively hot summers as climate changes could increase forest decline indirectly by soil acidification even when there is only a slight change in mean temperature.

The discussion above notes two particularly interesting pathways for interactions among stresses on forest ecosystems: enhanced oxidant abundances interacting both chemically and biologically with other air pollutants; and increased temperature interacting with enhanced soil acid loads to leach cations and mobilize soil metals. The large increases which may occur for H_2O_2 merit special attention since investigation of the phytotoxic characteristics of this oxidant are just beginning, and synergistic responses with other pollutants seem likely. H_2O_2 and other oxidants also will accelerate the production of acids in leaf droplets. It has been suggested that doubled CO_2 levels may increase stomata resistance by as much as 40%, reducing damage from gaseous pollutants.[21] It is unclear whether such an argument pertains to H_2O_2, which is highly soluble. Further, ozone and perhaps H_2O_2 affect plants synergistically with acid deposition on foliage.

Increasing UV-B itself represents a significant stress on vegetation. Inhibition of photosynthesis, mutogenesis, changes in patterns of competition, and yield reductions have been observed in plants at the molecular or community levels.[21,22] The interaction of these changes with climate or pollutant stresses is unknown, although it is known that increased fertilization and water stress decrease sensitivity to UV-B.[23] On the other hand, foliage damaged by air pollution or acid rain may be more vulnerable to UV-B.

Water availability stress in conjunction with air pollution stress has been cited as a possible cause of temperate forest decline.[20] Climate change offers the potential for such joint interaction in areas where soil moisture is decreasing. Models of forest shifts in response to moisture and temperature changes should consider pollution stressed forests as a base case, at least for the mid-latitudes.

The foregoing discussion has identified ways in which temperature, soil moisture, nitrogen and sulfur deposition, and increased UV-B interact synergistically to stress forests. The confluence of these stresses may be expected to accelerate change and biomass reduction already observed in temperate zone forests in industrial regions, in spite of the fact that nitrogen--frequently a limiting nutrient in forests--is increasing in deposition.

Mechanisms involving oxidants and nitrogen are of particular concern. Projected increases in nitrogen emissions will in turn increase nitrogen deposition and atmospheric ozone concentrations, just as temperature and UV-B changes stimulate ozone production. Climate warming and related forest disturbance may enhance mineralization of nitrogen and may accelerate acidification and increase nitrogen leaching. Some drainage basins in the United States already discharge a large fraction of deposited nitrogen, and degradation of these systems has important downstream consequences.[24] On the other hand, some feedbacks will be negative. Decay and nitrification may be slowed by acidic or drier conditions, and CO_2 increases may reduce pollutant interaction with foliage.

IV. CLIMATE CHANGE, FRESHWATER SYSTEMS, AND ACIDIFICATION

Freshwater systems in watersheds with non-calcerous soils are subject to acidification in industrialized regions due to enhanced sulfate and nitrate deposition, known as acid rain. This deposition is partly neutralized by weathered alkalinity and cations leached from soils. Climate change will alter precipitation rates and soil moisture content. It is unlikely that acid anion concentrations in precipitation will change sharply since long term concentrations of sulfate in precipitation are not strongly dependent on precipitation rate or volume.[25] Similarly, concentration of alkalinity in surface waters is not sensitive to flow (and hence precipitation rate) under a variety of low to moderate flow conditions. In contrast, soil cation exchange is highly sensitive to evapotranspiration rate. Simulations suggest that at a fixed precipitation acid concentration, soil solution pH varies seasonally by up to 0.5 units due to changes in evapotranspiration which alter acid anion concentrations in soil solution.[26] Therefore, it can be expected that climate change will accelerate soil and surface water acidification, even at constant precipitation acid concentration levels, in areas where runoff decreases. With increases in sulfur dioxide and nitrogen oxide emissions, this effect is enhanced. This interaction is synergistic in the sense that evapotranspiration changes in absence of mineral acids will have little effect on soil solution pH. We note that a preliminary analysis of this interaction by Tirpak[27] reached a different conclusion. Direct increases in surface water acidity due to atmospheric CO_2 changes may also occur, according to the dependence of weathering on H^+ concentration changes.

A temperature-dependent soil acidification mechanism due to increased nitrification was discussed in Section III. Such a mechanism indirectly affects surface waters. Acidification of lake waters may also increase due to alterations in the chemical oxidation rate in the lakewater column above sediments. The anaerobic reduction of sulfate appears to be an important source of alkalinity in many softwater lakes, sometimes contributing on the order of 1/2 the alkalinity.[28] The resulting Fe-S-H_2S system is highly coupled, and intervention by increasing oxidant concentrations will enhance oxidations in bioturbed sediments, as well as in the overlying water column, resulting in increases in both sediment and H_2S oxidation from reduced form to sulfate.[29] These transformations effectively reduce alkalinity. Increased oxidation removes Fe^{+2} from the water column, making it unavailable for pyrite formation. In addition, at H_2O_2 concentrations above 10^{-5} M, reaction with H_2S enhances sulfate concentrations. Such values may occur in certain freshwaters now, or in the future atmosphere discussed in Section II. Enhanced in situ oxidant formation may be important in waters high in organic carbon[30] while dissolution of oxidants from the atmosphere may be an important source in other waters.

The net effect of such changes would be a <u>decrease</u> in freshwater alkalinity. Sulfur additions to waters are partly counteracted by <u>increases</u> in sulfur reduction rates,[28] but rapidly increasing oxidant levels would have a countervailing effect.

Increased sulfur and nitrogen emissions and deposition will obviously accelerate acidification of sensitive waters. For the U.S., emission increases may be 30-50% beyond 2010 if no further control actions are taken.[31] In Europe, projected emissions control actions may reduce numbers of acidified waters, but this improvement will be counteracted by sulfur cycle changes due to enhanced oxidant levels. Much larger increases will occur in the developing countries with sensitive waters (cf. Table 1). In addition, soil moisture reductions associated with climate change will decrease pH in soil water. Enhanced oxidant levels from NO_x and hydrocarbon increases, and from UV-B enhancement will accelerate atmospheric photochemistry and freshwater and sediment chemistry, increasing acidity and decreasing production of alkalinity.

A crude estimate based on current surface water alkalinity distributions suggests that sulfur and nitrogen deposition changes alone would increase by a factor of two the number of acidified lakes in the U.S. The other simultaneous changes will substantially aggravate this situation. The synergistic interactions noted above, oxidant-interfence with the alkalinity production, temperature enhanced nitrification, and increased soil acidity with decreased flow, all occurring while acid deposition is increasing, may cause this value to be a significant underestimate. On the other hand, pH-dependent negative feedbacks in the N-cycle could slow acidification.[32]

V. CONCLUSION

Climate change will occur in the pre-stressed world. Stratospheric ozone depletion, tropospheric oxidant concentrations, forest degradation, acidification, and nutrient cycling will be enhanced by climate change. How these changes will affect temperate forests and freshwaters has been described and one conclusion stands out. In addition to difficulties which the direct effects of climate change may hold for human beings and natural ecosystems, the intensification of air pollution problems will be an important indirect consequence of a warmer climate where UV-B is also enhanced. A prominent concern is the effect of increased levels of atmospheric oxidants.

Two strategies for reducing the consequences of climate warming and ozone modification should be pursued immediately.

(i) Reduce vulnerability to future ecological stress by limiting NO_x, SO_2 and hydrocarbon emissions.
(ii) Limit the emissions of greenhouse gases and eliminate emissions of ozone-depleters.

TABLE 1

PHYSICAL SETTING				
WORLD				
	(1850)	1980	2030	
SO_2-S	(65)	65	205	ton S x 10^6/yr
NO_x-N	(30)	20	65	ton N x 10^6/yr
UNITED STATES				
SO_2-S	(<1)	13	17	ton S x 10^6/yr
NO_x-N	(<1)	6	9	ton N x 10^6/yr

SO_2-S and NO_x-N refer to SO_2 emissions (as sulfur) and NO_x emissions (as nitrogen), respectively. SO_2 and NO_x emissions are based on energy scenario projections[a] which lead to a 2.4%/yr growth rate for CO_2 emissions. A lower growth rate of 2.1%/yr has been suggested recently.[b]

Values under (1850) reflect total natural sources of atmospheric sulfur and nitrogen, not just SO_2 and NO_x. Values for later years reflect anthropogenic SO_2 and NO_x emissions.

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[a] R.M. Rotty and G. Marland. Constraints on Carbon Dioxide Production from Fossil Fuel Use, paper presented at Energy/Climate Interactions Workshop, Munster, Germany, March 3-8, 1980.

[b] R.M. Rotty and D.B. Reister, Use of Energy Scenarios in Addressing the CO_2 Question. J.A.P.C.A. 36, 1111-1115, 1986.

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POTENTIAL PUBLIC HEALTH CONSEQUENCES OF GLOBAL CLIMATE CHANGE

by

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Scenarios of global warming rivet public attention and routinely grace a number of national news publications. Beyond the dramatic projections of sea level rise and desertification (NRC, 1983a, 1987), no models of climate change thus far have addressed the potential for more subtle socioeconomic and public health impacts. In light of the mounting evidence on global warming and ozone depletion, this paper speculates about some possibly linked socioeconomic and public health consequences. The present lack of evidence on these questions should not be construed as evidence that such impacts are unlikely, but rather as a stimulus to develop appropriate models to assess them.

WILL WARMING CLIMATE INCREASE THE GEOGRAPHIC SPREAD OF INFECTIOUS DISEASES?

In 1979, Weihe suggested that climatic factors, such as temperature and humidity, play a more significant role in vector-borne diseases than in the transmission of contagious diseases, in that vector-borne diseases may well increase their geographic range with increased warming. Devastating insect-borne infections, such as dengue, yellow fever, malaria, and leishmaniasis, are more prevalent in the warmer tropical latitudes, reflecting clothing, sanitation and climatic conditions. Thus, epidemic typhus rarely occurs in cold climates. Temperature-dependent Clostridium tetani spores, distributed in the soil, result in the highest rates of morbidity occurring in the warm countries near the Equator.

With warming climate, changes in soil moisture and microbial communities may well expand the ranges for exposure of humans to tropical infectious agents. Food-borne diseases are also more prevalent in the tropics than the temperate world, in part because ecological conditions foster their propagation, and also because of profound socio-economic disparities. Since industrial societies have more developed technologies that minimize infectious diseases, those that experience global warming will not ipso facto experience increased rates of tetanus and other such infections; but, in less developed countries that experience warming, such infections may well become more prevalent.

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If tropical conditions expand geographically, changes in the prevalence of all such diseases will need to be monitored carefully. It is important that models be devised to estimate the effect that global climate change could have on infectious disease patterns, taking into account socio-economic differences. Health care planners in developed and developing countries could then utilize these models to formulate health care strategies.

WILL INCREASED UV-B RADIATION INCREASE CANCER AND ADVERSELY AFFECT AGRICULTURE?

Stratospheric ozone, which prevents the most damaging ultraviolet wavelengths from reaching the Earth's surface, is the only important atmospheric absorber for UV-B radiation between 280 and 320 nm (the wavelength of the ultraviolet portion of the solar spectrum spans from 200-400 nm). Of the solar energy that reaches the earth's surface 1.5% is composed of UV-B radiation (WHO, 1979). This portion is responsible for a series of recognized biological effects, including skin cancer, sunburn, and inhibition of cell mitosis (Kornhauser, 1987).

A decrease in stratospheric ozone levels could result in an increase of UV-B radiation at the planet's surface (Rowland, 1987;Bowman, 1988). The National Research Council has estimated that each 1% depletion of ozone would result in a 2% increase in cancer-producing ultraviolet radiation, and a 4% increase in skin cancer after several generations (NRC,1979).

It is possible that food chains may also be affected by increased UV-B, since radiation could affect the productivity of plants and weeds. Impacts on marine algae, which are also sensitive to UV-B radiation, might affect our supply of edible fish (UNEP 1987a).

WILL INCREASED UV-B AND OTHER POLLUTANTS ADVERSELY AFFECT THE IMMUNE SYSTEM?

Recent developments in the field of immunotoxicology indicate that UV-B and a number of pollutants can adversely affect the ability of the body to defend itself against disease. Some studies suggest that suppression of immune response occurs in humans after exposure to UV-B radiation, thus leading to the development of light-induced skin tumors (Kornhauser, 1987). Kripke (1980) found UV-induced alterations of immune function in mice. Mice exposed to low doses of UV-B showed increased susceptibility to a transplanted tumor, while mice without such exposures rejected the transplants. In light of the recent analysis of Bowman, 1988, that ozone depletion is occurring world-wide, models are needed to estimate the effects that increased UV-B may have on immune suppression and potential increases in a host of infectious diseases, such as those indicated in Table 1.

In addition, to the potential immune suppressing effects of UV-B, other tropospheric or environmental pollutants such as ozone, benzo-a-pyrene, nitrogen oxides, and sulfur oxides, have also been linked with immunotoxicological effects, as Table 2 shows (Berlin et al., 1987).

TABLE 1 Examples of communicable diseases: non-contagious infections

Insect-Borne Infections

Name	Vector
Yellow fever	Mosquito (Aedes aegypti)
Dengue fever	Mosquito (Aedes spp.)
Malaria	Mosquito (Anopheles)
Filariasis	Mosquito
Wuchereria bancrofti	(Culex, Mansonia, Aedes)
Loa loa	(Chrysops)
Onchocerca volvulus	(Simulium)
Leishmaniasis	Sandfly (Phlebotomus)
Bartonellosis	Sandfly (Phlebotomus)
Afr. trypanosomiasis	Tsetse fly (Glossina)
Amer. trypanosomiasis	Bug (Triatoma, Panstrongylus)

TABLE 2 Some chemicals affecting the immune system in experimental animals

Chemical	Effects
Benzo(a)pyrene	Decrease in the number of antibody forming cells; decreased lymphocyte proliferative responses to both T cell and B cell mitogens
Cadmium	Decreased and increased resistance to certain bacterial, viral and tumor challenge; decrease and increase in number of antibody forming cells; decreased and increased serum antibody titers; inhibition and enhancement of macrophage functions; decreased and increased lymphocyte proliferative responses to mitogens
DDT	Increased susceptibility to infection; decreased serum antibody titer; depressed IgM and IgG levels; decreased propensity to develop anaphylactic shock
Hexachlorobenzene (HCB)	Decreased host resistance to infections; increased number of circulating monocytes; decreased and increased humoral immunity
Lead	Impaired antibody synthesis and cell-mediated responses; decreases resistance to infectious or neoplastic challenge; depressed B cell proliferative response to mitogen;
Mercury	Decreased host resistance to infectious or neoplastic challenge; decreased antibody response; depressed T cell lymphoproliferative response to mitogen
Ozone	Decreased macrophage function; decreased resistance to infection; decreased T cell proliferative response to mitogens; enhancement of allergic sensitization; in humans - reduced phagocytic function; decreased T cell proliferative response to mitogen; decrease in B cells

Berlin et al., 1988.

Experimental studies indicate that low concentrations of nitrogen dioxide and ozone lower resistance of animals to bacterial infection, and thus maylead to increased rates of viral and microbial infections in humans. There is need to consider a possible interaction between vectors for those infectious diseases and increased exposure to the immunosuppressive effects of UV-B radiation and other pollutants.

Further compounding the potential for linking immunotoxicological disturbances with changing climate is the fact that infectious diseases, in their own right, have effects on immune function. More than 400 distinct microorganisms can infect humans. By the time of death, each of us has typically been subjected to about 150 such infections. (Burnet and White, 1978). Thus, models of the relationship of climate and public health need to consider multiple interactions that may occur, among increased tropospheric pollutants, expanded vectors for infectious diseases, and greater overall exposure to UV-B. Any one of these factors will affect immune function. The effect of all of them together remains an important unknown.

POTENTIAL FOR INCREASED TROPOSPHERIC AIR POLLUTION

With increased warming, the developed world may well use more fossil fuels for cooling, thereby increasing tropospheric pollution. Carbon dioxide, water vapor, ozone, methane, and nitrous oxide are some of the so-called "greenhouse gases," produced by fossil fuel consumption, that are transparent to incoming shortwave radiation but effective absorbers of the infrared longwave radiation emitted by the Earth's surface (NRC,1983a).

Ozone, sulfur dioxide and total suspended particulates are toxic to the respiratory tract and are linked to increased rates of infection in children, increased hospitalizations for respiratory problems, and decreased pulmonary function. Long term consequences of the public health impacts of this increased pollution are uncertain but may result in chronic impairment at later ages (NRC, 1984). On the basis of data covering 1974 to 1983, Bates and Sizto (1987) reported that "there is a consistent relationship between sulfates, ozone and temperature, and respiratory admissions with or without asthma". Ware et al. (1986), as part of the Harvard Study of Air Pollution and Health which was begun in 1974, reported that exposure of preadolescent children to "moderately elevated concentrations" of total suspended particulates (TSP), the sulfate fraction of TSP, and sulfur dioxide, "increases risk for bronchitis and some other respiratory disorders, but had little or no effect on pulmonary function level." Lippman et al. (1983) of New York University determined that when young children at summer camp are exposed to increased levels of ozone, consistent decreases in pulmonary function were observed, especially in indices of expiratory lung function. Whitten and Gery (1986) postulated that in polluted urban areas there will be increased UV-B penetration into the troposphere, due to decreases of atmospheric ozone in the stratosphere. There will be increased ozone in the troposphere as more precursors of ozone are formed from burning forests and lightning.

METEOROLOGICAL PARAMETERS THAT INFLUENCE HUMAN HEALTH

The many variables of climate such as temperature, wind, precipitation, humidity, and air pressure--individually or in combination--tend to affect human health. Changes in morbidity and mortality patterns may occur with increased mean temperature and increased extremes of weather.

During summertime the combined effects of high temperatures and high humidity tend to make people sluggish, irritable, and very uncomfortable (Nicodemus et al., 1987). Applegate et al (1981) reported on the Summer 1980 heat wave in Memphis, Tennessee when the temperature remained above the mean for 27 days. Eighty-three heat-related deaths were noted, as compared to none during the same month of earlier years. The poor, the elderly, and inner city residents, especially those with previous medical conditions, bore the brunt of the heat wave.

Patients with multiple chronic diseases such as cardiac problems and diabetes tend to develop fluid imbalances easily. With increased heat, such imbalances occur more easily and may lead to serious increases in morbidity. Questions have also arisen as to how climate affects human behavior. Prolonged heat waves have long been linked with social pathological behavior such as murders. The clinical status of patients suffering from a wide variety of mental instabilities, including neuroses, is often aggravated during periods of extreme weather conditions.

For those with allergic and other respiratory problems, winds may be especially troublesome since they may carry pollen, dust and other irritants to the respiratory system (Nicodemus et al., 1987). Palmer (1976) indicated that windspeeds above 20 mph inhibit human activities and can cause severe discomfort.

POSSIBLE INCREASE IN FLOODS, FIRES, DISRUPTION OF INFRASTRUCTURES

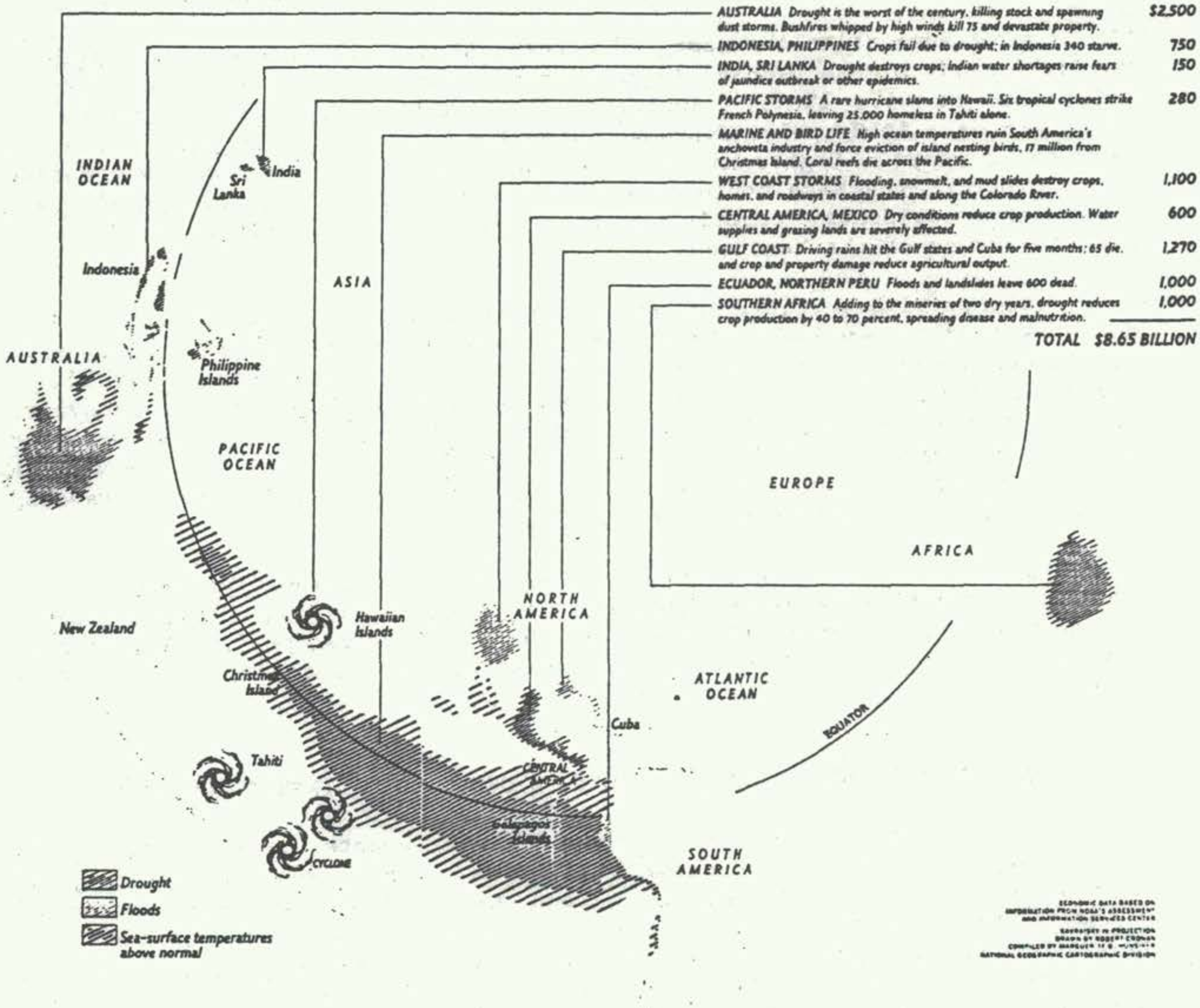
The frequency and severity of some extreme events, such as floods and fires, may be affected by climatic changes. The occasional warming of coastal waters off South America known as El Niño has been linked to anomalies in temperature and precipitation around the world (NRC,1983b). Meteorological and ecological effects associated with the 1982-1983 El Niño event resulted in major socioeconomic and ecological disruptions which affected the lives of many millions of people around the world (See figure 1). Given that some two-thirds of the world's population is without clean water (UNEP, 1987b), El Niño created a great deal of social and economic distress, as well as increases in outbreaks of infectious diseases.

According to some global circulation and radiative convective models, increased mean temperatures may lead to drier air over some large land masses, which could increase the likelihood and frequency of fires. With warmer temperatures, winds may also be increased. As soil moisture content may shift, areas with sufficient long-established forests may undergo some drying. Flash points of these drying forests may be reduced, leading to increased incidence and magnitude of fires. Climatological shifts may also result in less surface water being available to control fires.

EL NIÑO'S GLOBAL IMPACT 1982-83

THE WORST of it was the loss of human lives to floods, fires, and starvation, which no accounting can reckon. Yet the mounting statistics of crops destroyed, of livestock killed, of birds and marine life vanished, lengthened the ledger of misery. There was some solace; massive El Niños are not prone to develop in close succession, and the century's most destructive seemed to be dissipating.

	DAMAGE in millions of dollars
AUSTRALIA Drought is the worst of the century, killing stock and spawning dust storms. Bushfires whipped by high winds kill 75 and devastate property.	$2,500
INDONESIA, PHILIPPINES Crops fail due to drought; in Indonesia 340 starve.	750
INDIA, SRI LANKA Drought destroys crops; Indian water shortages raise fears of jaundice outbreak or other epidemics.	150
PACIFIC STORMS A rare hurricane slams into Hawaii. Six tropical cyclones strike French Polynesia, leaving 25,000 homeless in Tahiti alone.	280
MARINE AND BIRD LIFE High ocean temperatures ruin South America's anchoveta industry and force eviction of island nesting birds, 17 million from Christmas Island. Coral reefs die across the Pacific.	
WEST COAST STORMS Flooding, snowmelt, and mud slides destroy crops, homes, and roadways in coastal states and along the Colorado River.	1,100
CENTRAL AMERICA, MEXICO Dry conditions reduce crop production. Water supplies and grazing lands are severely affected.	600
GULF COAST Driving rains hit the Gulf states and Cuba for five months; 65 die, and crop and property damage reduce agricultural output.	1,270
ECUADOR, NORTHERN PERU Floods and landslides leave 600 dead.	1,000
SOUTHERN AFRICA Adding to the miseries of two dry years, drought reduces crop production by 40 to 70 percent, spreading disease and malnutrition.	1,000
TOTAL	**$8.65 BILLION**



ECONOMIC DATA BASED ON
INFORMATION FROM NOAA'S ASSESSMENT
AND INFORMATION SERVICES CENTER
[illegible] PROJECTION
DRAWN BY ROBERT CRONAN
COMPILED BY [illegible]
NATIONAL GEOGRAPHIC CARTOGRAPHIC DIVISION

FIGURE 1 El Niño's global impact 1982-83
Canby, 1984

The severe droughts which occurred in Africa, Asia, and South America during 1982 -1983 showed how vulnerable societies were to variations in climatic temperatures and precipitation (Glantz, 1987). He wrote that "many observers now believe that famines are a direct result of meteorological drought, arguing that a lack of rainfall reduces agricultural production which leads to reduced food availability in the marketplace which in turn leads to famine."

CONCLUSION

Little data exist on the topics sketched here. Developing valid models will pose a serious challenge to researchers, as a number of complex parameters are involved. Given the global nature and importance of these questions, serious efforts should be initiated to assess the possible public health consequences of climate change.

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LIKELY EFFECTS OF GLOBAL WARMING ON WATER AVAILABILITY AND HYDROLOGY IN NORTH AMERICA

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ABSTRACT

The projected future climate changes will likely have a significant impact on water availability in the United States. Because of the estimated size and rapidity of the forecast changes, there are no good analogs to provide indications of what we should expect. Thus we have to depend on imperfect models. Different modeling groups produce somewhat different results, and a set of experiments using the GISS global climate model with varying model resolution, model sensitivity, and the latitudinal response show that even the same model can produce different forecasts. Nevertheless, modeling experiments do show a tendency for wetter conditions in the northern part of the United States, with drying in the central, southern and eastern regions during some seasons. Additional experiments with improved models need to be performed to determine how robust these results are.

Introduction

A significant climate change impact on water availability is a distinct possibility in the coming decades. All modeling efforts are indicating substantial warming, unprecedented in historical times. A warmer climate will likely lead to increased evaporation, as warmer air can hold more moisture; while the effect could be mitigated by decreased surface winds or increased atmospheric relative humidity, modeling efforts suggest that evaporation increases should occur. The question of future water availability thus revolves around the uncertainty of what will happen to precipitation, both for the annual mean and the seasonal variation.

The Question of Analogs

To assess the prospective climate change impact on water availability, two approaches have been followed. The first is basically empirical: find times in the past when the climate has been warmer than today, and see what happened to the hydrologic cycle or its expression in various regions. As indicated above, there have been no historical times when the climate was as warm as is projected for the next century, but there have been relatively warm periods, such as the decade of the 1930s. That time was characterized by extreme droughts in both the Great Plains ("dust bowl region"), and in Siberia. It has led to speculation that drying of mid-latitudes in summer is a feature of warm climates. Another warmer period (at least in summer) occurred about 6,000 years ago, the "climatic optimum"; it too was characterized by reduced water availability as indicated by lower lake levels at specific mid-latitude locations in the southwestern United States (Street and Grove, 1979). Independent of large scale climate changes, empirical relations can be formulated for the relationship between hydrologic parameters such as streamflow and temperature/precipitation in given regions (e.g., Langbein 1949). Revelle and Waggoner (1983) have used these relationships to calculate that an increase of 2°C would result in approximately 30% decrease in river runoff.

The difficulty with using these other times as analogs is that the reason(s) for the warming in these intervals is not known, or is substantially different from that expected to occur during the next century. It is possible that the 1930s were warmer due to the internal dynamics of the system; if so, a system which is forced to be warmer radiatively may well react quite differently. During the climatic optimum, solar radiation conditions differed from the present due to changes in the orbital configuration of the earth and sun. Solar changes for specific seasons and latitudes represent very different radiative forcing changes than the greenhouse gas increase, whose radiative effect is felt at all latitudes in all seasons.

Another difference between past and future changes concerns the magnitude and time scales involved. The warming during the first part of this century was very small (a few tenths of a degree C), gradual, and short-lived (less than 50 years). The climatic optimum was probably on the order of 1°C warmer on the global average than today, and the warming developed over a much longer time (probably thousands of years). The projected warming is much larger in amplitude than the historical change, and much more rapid (and perhaps larger) than the second. Different parts of the climate system (ice, oceans, ground) have different time scales of response, and it is not possible to learn from these other time periods how the system as a whole will operate during the next several decades, the transient phase of the warming. To summarize, then, while potential analogs should be scrutinized, the inappropriateness of these other time periods to represent the future situation prevents their being used for any practical determinations.

Modeling Results

The other major approach available is to integrate general circulation models (GCMs) with increased trace gas concentrations, and let the model indicate what will happen to water availability. Kellogg and Zhao (1987) reviewed the different model results for doubled CO_2, and while there was variability from model to model, the concensus was that in winter there may be an increase in water availability in North America at high latitudes, with drier conditions in the south, and in summer there may be a tendency toward drier conditions in the middle of the continent with wetter conditions along the west coast. However, there are many reasons to be wary of accepting the model results at this time. Primary questions still surround the accuracy of the models' sensitivity to doubled CO_2; while all the models produce global temperature increases of 4±1°C when cloud feedback is included, the cloud feedback is very crudely modeled, and may contribute up to 50% of the result. Different models get different amounts of high latitude amplification of the warming effect, which will affect model assessments (Rind, 1987a). Models are run with relatively coarse horizontal resolution, and the results for individual areas may well depend on the size of the individual regions being modeled.

To investigate the influence of these factors on modeled changes, Rind (1987b) looked at the difference in water availability over North America for a variety of doubled CO_2 climate change experiments using the Goddard Institute for Space Studies (GISS) global climate model. In particular, the dependence on sensitivity was addressed by looking at two model experiments in which the magnitude of the warming differed, due to different treatments of sea ice, with annual average global surface air temperature increases of 4.2°C in one case, and 4.8°C in the other. Experiments were run with specified magnitudes of high latitude amplification (high latitude/low latitude warming) which differed by a factor of 2, and also with different model resolutions. The range of parameters used in these different experiments is representative of the differences currently being produced by GCMs today in their assessment of the doubled CO_2 climate.

The results show that the degree of drying over land during mid latitude summer is dependent upon the degree of high latitude amplification. With greater warming at high versus low latitudes, there is a decrease in the storms which carry moisture from low latitudes, and a decrease in the convergence of moisture over mid latitudes. In addition, without a large magnitude of low latitude warming, there is not as much additional moisture available in the warmer climate for rainfall. While the effects are more pronounced in seasons other than summer, the hydrologic system is capable of extending winter and spring changes into the summer season. For example, decreased moisture convergence and earlier warming in spring reduces the late spring snow melt, which affects early summer moisture availability.

The assessments also depend upon the model resolution and magnitude of warming, as storm tracks shift to somewhat different locations in the different runs, and the present climate control runs from which changes are being calculated are somewhat different. The results for the western United States depend most on model resolution; those for the central United States, on the latitudinal gradient of the sea surface temperature warming; and those for the eastern United States on model sensitivity. There is thus much variability in the change of water availability, especially on the grid box spatial scale.

However, there is a general tendency in the experiments for the northern and western United States to become wetter, while the southern and eastern portions dry (and, illustrative of the influence of model resolution, the extent of the wetter climate in the west is more restricted to near-coast effects with the finer resolution model). The overall result is not qualitatively different from that produced by a concensus of current models, although the magnitude and even the sign of change for a specific area can be quite variable. The results thus provide some hope that assessments of future water availability will be possible in advance of their actual occurrence. The dependence of changes in a particular season on changes in other seasons emphasizes the need for improved ground hydrology models, which are currently very crude.

Conclusions

In summary, model assessments of changes in future water availability are probably the only means available for providing forecasts as we move into an unprecedented climate state. Current model results indicating wetter conditions to the north, with drying in the continental interior and to the east and south in some seasons, cannot at this time be accepted at face value. However, as more experiments are performed to increase our understanding of the sensitivity of these results to uncertain modeling aspects, we should be able to determine the robustness of such forecasts and their regional applicability. The likelihood of significant changes in regional water availability occuring is high, and given the potential consequences of any changes, we must focus on improving our ability to provide meaningful predictions as quickly as possible.

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Presentation

Adjusting Water Allocation Law to Meet Water Quality and Availability Concerns in a Warming World

First North American Conference
on
Preparing for Climate Change:
A Cooperative Approach
October 29, 1987

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Denver, Colorado

Introductory

Today I find myself in a most unaccustomed situation--being one of the few lawyers in a roomful of scientists in Washington, D.C.! So you must forgive me if I seem a bit off balance in this most unusual setting.

The question before us this morning puts me, as a lawyer, in an unusual situation in other ways, as well. We are examining an environmental phenomenon with multifarious potential impacts and are attempting to craft avenues by which society may choose to anticipate and ameliorate the foreseeable effects of those impacts. The first problem, of course, is that the "foreseeable impacts" are themselves in dispute. Science appears unable to provide those working in the law with the factual certainty we think is necessary before we can envision potential legal change. There appears to be an unavoidable conflict or at least dissonance between the scientists who think in terms of aggregates and probabilities, and the lawyers who think in terms of individuals and certainties.

For purposes of discussion, we must make assumptions. In considering the question of water supplies in the western United States, I will assume that Dr. Revelle's well-respected work, suggesting that water supplies in the West will be dramatically imperilled, represents a future for which we now must begin to plan.[2] Even if there is reasonable doubt about Dr. Revelle's findings, the possibility that climactic change could result in a forty percent reduction of water supplies in the upper Colorado poses an awesome challenge for the Rocky Mountain region in particular.[3] I will also make a legal assumption for discussion purposes, that the "Colorado Doctrine" of water law applies throughout the West--even though, as our friends from California will be the first to remind us, the law varies significantly among some of the western states.

Western Water Law: The Appropriation System

As we all know, much of the arid western United States was made habitable as a direct result of government action to provide the predictable supplies of water required for human habitation and resource development. The history of the West, particularly the Rocky Mountain West, is literally a history of water development.

Western water law vividly reflects the distinction between the needs of the arid West and those of the eastern states in which water is plentiful. In the eastern states, water law developed along theories of "riparian rights," which has several bases: (1) it is linked to the ownership of land bordering a waterway; (2) "reasonable use" may be made of the water, subject to the rights of other, similarly situated landowners; (3) landowners may not be lost even if they are not utilized at a given time.

Western states, on the other hand, originated the doctrine of "prior appropriation," which was understood to better meet the need for rapid development in the midst of limited water supplies. The link between ownership of bordering land and water rights was severed. Also, rights to water that was not put to "beneficial use" could be lost to others who were able to make beneficial use of the water. Three elements are therefore required to perfect a water right under prior appropriation doctrine: (1) an <u>intent</u> to apply water to a <u>beneficial use</u>; (2) an <u>actual diversion</u> of water from a natural source; and (3) the <u>application</u> of the water to a <u>beneficial use</u>.[4]

A. Beneficial Use:

The first problem that would likely arise from a new shortage of water in the West would be new difficulties in determining what constitutes a beneficial use. Agricultural, industrial, domestic and municipal water uses would no doubt continue as beneficial uses, but newer uses, such as recreational uses or federal reserved water rights, might come under more attack because of an absence of highly motivated and organized political support.[5] It is also possible that even confirmed uses could be eliminated or dramatically affected because of lower flows--and there would likely be additional problems with water quality resulting from lessened dilution.

B. Priority of Appropriation

A significant decrease in water supply would also strain the "first in time, first in right" principle of the Colorado Doctrine, under which those users with senior water rights have priority over those which come later. Although in theory transactions can be accomplished allowing more "economically efficient" uses to prevail over "less efficient" uses through the purchase of senior appropriators' water rights, such transactions are often difficult and expensive as a practical matter. A major decline in water quantity would likely lead to efforts to reform such laws toward a more market oriented approach. Whatever approach is taken, the bottom line is that the principle of priority of appropriation will be placed under severe stress.

C. Equitable Apportionment and the Law of Prior Appropriation

The Colorado Doctrine--indeed the very notion of state control over water supplies within state boundaries--will also face, in the event of a major water shortage, an unparalleled challenge from foreseeable interstate disputes. This challenge is foreseeable, because a significant decrease in flows would merely accentuate interstate disputes that have long marked the history of the western states.

In resolving interstate disputes, a federal common law of "equitable apportionment" has developed, which the Supreme Court has described as a flexible doctrine relying on "the exercise of an informed judgment on a consideration of many factors" to secure a "just and equitable" allocation.[6]

In a recent case, Colorado v. New Mexico,[7] the Supreme Court applied the doctrine and refused to apply strict priorities in a dispute between two states with appropriation systems, since the effect would have been to protect arguably wasteful and inefficient uses in New Mexico at the expense of arguably more efficient uses in Colorado. The Court explained that equitable apportionment will protect only those rights which are "reasonably required and applied."[8] This rule is to be applied "[e]specially in those western states where water is scarce... [t]here must be no waste... of the treasure of a river...only diligence and good faith will keep the privilege alive."[9] The decision also enumerated the factors to be considered in achieving an equitable allocation, including:

> physical and climactic conditions, the consumptive use of water in the several sections of the river, the character and rate of return flows, the extent of established uses, the availability of storage water, the practical effect of wasteful uses on downstream areas, [and] the damage to upstream areas as compared to the benefits to downstream areas if a limitation is imposed on the former.[10]

The Court's reasoning--and the explicit mention of climactic conditions--leads to the conclusion that traditional notions of prior appropriation could fall by the wayside in the midst of major flow reductions from climate change. Consequently, this may lead to a balancing of interests in any given dispute. The holding in Colorado v. New Mexico that reasonable conservation measures could offset injuries which might otherwise result from in New Mexico from Colorado's use of water may presage further direct judicial intervention in the event of climate change. While the implications can only be guessed, it would appear that some of the oldest and least "efficient" uses--such as those often found in the agriculture sector--would be pushed rapidly toward new techniques of water usage.

Just as equitable apportionment may be used to override priorities in interstate disputes, so may it be used in intrastate disputes. The Supreme Court of California, for example, has cited the equitable apportionment principles used by the United States Supreme Court for that very purpose.[11]

Looking Ahead: Climate Change and Western Water Rights

It is clear that the projected climate changes in the Rocky Mountain West could be anticipated, without exaggeration, to lead to social and legal dislocation of a major magnitude. Needless to say, the interrelationships between the state and federal governments, and between private parties dealing with government--as well as relations with bordering nations and Indian tribes--would be dramatically affected. In such a situation of rapid change, it can be expected that the western water allocation system, which grew in a time during which the acknowledged need of society was to divert water primarily for development purposes, will in turn be altered. Further, existing interstate compacts and judicial decrees would likely come under challenge. Generally, it is foreseeable that both interstate and intrastate disputes over water use would be heightened in the face of water shortages, and that mechanisms such as equitable apportionment and market transfer systems would be interposed with the existing prior appropriation legal regime. The specifics of the mechanisms chosen would likely reflect the degree of scarcity relative to accepted needs.

The effects of limited water supplies would of course go far beyond the confines of what is considered to be "water law." Resource development generally (which is closely related to water availability and needs), population growth, land-use planning and the entire agricultural sector would all be directly affected.

What is clearly needed now is a "pro-active" effort to increase the knowledge about global warming in the hope of achieving a scientific consensus with sufficient certainty to allow politics--which, ideally, is concerned about the future--to influence the law--which generally brings stability and predictability to established societal relationships and expectations. Needless to say, the historical precedents for such far-sighted actions are distressingly limited. Instead, American government has relied upon what Professor Haar has called the "catastrophe theory of planning"--precipitate action follows a crisis of sufficient magnitude to shake existing arrangements.

In the case of global warming and climactic change, the potential catastrophe is greater than most in the past, and, in turn, we much act with greater resolve and foresight than in the past. This will require unprecedented cooperation and understanding between the state and federal governments, and the disciplines of science and law.

Endnotes

1. James M. Strock practices law with Davis, Graham & Stubbs in Denver, Colorado. Previously he was Special Counsel to the Committee on Environment & Public Works, U.S. Senate, and Special Assistant to the Administrator, U.S. Environmental Protection Agency.

2. _See_ Revelle & Waggoner, "Effects of a Carbon Dioxide-Induced Climactic Change on Water Supplies in the Western United States," in _Changing Climate_, Report of the Carbon Dioxide Assessment Committee, National Academy of Science (1983) (finding, at 419, that "warmer air temperatures and a slight decrease in precipitation would probably severely reduce both the quantity and quality of water resources in the western United States).

3. _Id_. at 424.

4. For a review of common law development of "Colorado Doctrine" of prior appropriation, _see_ Colo. Rev. Stat. 37-82-101 _et seq_. (1973 & Supp. 1986) and annotations thereto.

5. Of course, predicting future decisions on beneficial uses is fraught with difficulty, in part because what is considered to be a beneficial use may change. Thus, at the turn of the century, a federal court refused to consider recreation a beneficial use in the case of a waterfall which was a tourist attraction to Cascade, Colorado. _Empire Water & Power Co. v. Cascade Town Co._, 205 F. 123 (8th Cir. 1913).

6. _Nebraska v. Wyoming_, 325 U.S. 589, 618 (1945). Equitable apportionment was initially enunciated in _Kansas v. Colorado_, 206 U.S. 46 (1907).

7. 456 U.S. 176 (1982).

8. _Id_. at 184.

9. _Id_., quoting from _Washington v. Oregon_, 297 U.S. 517, 527 (1936).

10. Id. at 183, quoting from Nebraska v. Wyoming at 618. (emphasis added).

11. See City of Los Angeles v. County of San Fernando, 537 P.2d 1250 (Cal. 1975).

AN ARMY CIVIL WORKS PERSPECTIVE ON RESPONDING TO CHANGING WATER AVAILABILITY

REMARKS OF DR. G. EDWARD DICKEY*

PANEL ON
CLIMATE CHANGE AND WATER AVAILABILITY
FIRST NORTH AMERICAN CONFERENCE
ON PREPARING FOR CLIMATE CHANGE
WASHINGTON, D.C.
OCTOBER 29, 1987

I appreciate the opportunity to participate in today's panel. We in the Army Corps of Engineers are often accused of taking too long a view of our Nation's requirements. By the standards of this program, however, we are "short-timers," concentrating on problems which affect our current citizens. Some might argue that we do not pay sufficient attention to the long-term effects of climate change. In my remarks today, I would like to define our current policies and evaluate the effect that climate change should be having on our programs.

The primary mission of the Civil Works program of the Army Corps of Engineers is the efficient management of the Nation's water resources as they relate to flood control and navigation, and to water supply, hydropwer, and recreation as these outputs can be related to the basic flood control and navigation purposes in multiple-purpose development. Changes in climate would have substantial effects on these resources. Consequently, the Corps has the responsibility to consider these changes, to understand the impacts which will result, and, within the context of existing budget constraints, to structure its program so as to minimize the adverse impacts.

Ultimately, global warming and the associated climatic changes are likely to have significant implications for the water resources of any particular region. Changes in temperature, distribution of rainfall, soil moisture, flood stages, and drought severity are possible. Weather extremes may become more frequent and prolonged. Climate-induced shifts in agricultural production, economic activity, stream flows, and sediment loads will affect our inland navigation program. The size and use of reservoirs will be affected by changes in hydrologic variables and by changing water demands. It may be necessary to reassess our policies by which we establish our choice between the so-called nonstructural solutions, relocation and alternative land use and structural solutions, construction of projects which allow existing land use to continue without suffering from weather extremes.

Although long-term climate changes will have important consequences, the effects of variation in weather produce far more dramatic results. Short-term weather variability continually presents the Corps with challenging hydrologic extremes.

In response to these challenges, existing reservoir systems have been designed to be resilient in response to extremes in weather variability. For these systems, the Corps also develops emergency water plans and drought contingency plans. We performed dam safety analyses that focus on the dam's abilities to withstand extreme flood events. We propose the reallocation of water storage to respond to changes in the array of demands served by the project.

For new projects, the Corps performs sensitivity analyses of how a project performs under alternative hydrologic assumptions. We design and select projects that perform well under a variety of alternatives.

The Corps of Engineers traditionally has modified the behavior of water; now we also recommend nonstructural solutions -- measures that modify human behavior. In flood and storm damage reduction, the Corps recommends flood-proofing, evacuation, wetland acquisition, flood warning, and emergency preparedness measures that can be implemented in conjunction with local planning and management programs. In water supply, the economic efficiency of water conservation measures is evaluated in conjunction with supply alternatives. In navigation, cargo handling, scheduling, and vessel management, options are evaluated in conjunction with channel, harbor, and waterway improvements.

In summarizing our activities, it is accurate to characterize our program as emphasizing weather variability rather than climatic change. Although some might question this emphasis, I believe the current problem solving orientation of the Corps is sound public policy. I offer three reasons for this conclusion.

First, climatic changes evolve over a long period of time. As our time horizons expand outward, the level of uncertainty increases. We simply do not know what the world will be like very far into the future; preparing for the future involves a risk that public investments will be wasted on ineffective projects.

Second, people have the ability to adjust to long-run changes in ways that are not possible in the shorter run. Public sector initiatives are most important when events cause abrupt changes that can create widespread hardships. They are less important when the private sector has more time to adjust.

Obviously, the future will not be the same as the present, and for many more reasons than climate change alone. Just as we should assume that climate will change, we also must assume that the human activities affected by climate change will change.

Geographic shifts in population and industry, shifts in consumer preferences, and technological change may well determine the impacts of climate change on the world of the future as much as will the fact of climate change itself. For instance, a region may begin to experience more frequent days of extreme temperature and more frequent and severe droughts. We should not assume that the best solution is to increase water storage, especially far in advance. The economy of the region may shift away from water-consuming agricultural production. Industry may adapt by acquiring water from the agricultural buffer. Price rises may reduce water and power uses. Net out-migration may take place. Existing water supplies can be better managed to account for more frequent periods of drought.

Our political and economic systems are flexible, and the long-term nature of climate change makes the problem more politically manageable and lowers political costs, since institutional change need not be traumatic. Time, accompanied by gradual adaptation and growth in our institutional capabilities, is, perhaps, our greatest reserve.

For instance, look at the dramatic progress that is being made to improve the marketability of water rights. Today, people in the water resources community are seriously talking about open market purchases, exchanges of water rights, and purchase of water rights options for insurance purposes -- things that would have been dismissed out-of-hand ten years ago. State and sub-state water management capabilities and technical expertise also are growing, and these units of government have the tools -- water rights administration, rate-making powers, and water development programs -- to adapt and respond.

The pressures of the future on water resources -- whether climate-driven or otherwise -- will enhance the role of markets in resource allocation. Market systems give us the flexibility to respond to changing conditions of demand

and supply. Admittedly, there are still serious obstacles to treatment of water as a commodity; barriers to interbasin and interstate transfers; the existence of unquantified indian river rights; and water rights and contract commitments. But gradually, I think, we will see the remaining obstacles removed and water will move to the most efficient use with greater ease than is possible today.

My third and final reason for supporting the Corps current emphasis on short-term problem solving -- this is one of the few forums where Corps solutions to water problems might be classified as "short term" -- is that we have an obligation to ourselves that exceeds our obligation to future generations. We should put more value on a payback to a public project that occurs this year, to one that occurs 50 or more years in the future. This is reflected in the Corps current planning procedures.

Our projects are typically designed for a 50-year economic life before major rehabilitation or replacement is required. Each project must be justified based on the present discounted value of project benefits and costs. Most important to this calculus, future benefits and costs are discounted; that is reduced at a compound interest rate which is currently about nine percent after inflation. The formula for computing the discount rate annually is fixed in law.

At a nine percent discount rate, the present value of a future dollar falls pretty fast as the future dollar becomes more distant. A dollar a year for 50 years is worth only 12 dollars in present value terms, and the first 6 dollars of present value are realized in the first 8 years. With some simplification, that is equivalent to saying that the Corps of Engineers economic planning horizon is, for all practical purposes, set in law at around 15 or 20 years. Economic benefits and costs beyond that time horizon have a minimal impact on the Corps project decisionmaking. By implication, long-term climate change is heavily discounted by economic accounting conventions.

Even if the planning horizon is effectively extended through the use of a lower discount rate, the uncertainties of the far future may still militate against immediate action.

This is and will continue to be an era of scarce budget resources, which means three things: we will never be able to do everything we want to do; the things we will want to do will emphasize costs spread out over time rather than large, up-front capital expenditures; and any expenditure we make will need to have a high and reasonably certain payoff.

Despite our emphasis on weather variability, this does not mean that we can, or should, ignore long-term climatic effects. In fact, within the current political and budgetary constraints, the Corps is directing some of its attention to these problems.

It seems to me that our first possible line of defense should be prevention through behavior modification, although our abilities here may be quite limited. Even if significant impacts are far off and uncertain, it is possible that some preventive actions can be justified because the potential payoff is high and the cost low. Other preventive actions could be justified because they provide other benefits, such as the reduction of health hazards or the protection of species. As time passes and our information improves, further actions may be justified.

We have accumulated valuable experience in working with the public in putting into effect the so-called nonstructural solutions to current water supply problems. If people can be shown why modifying their behavior can lead to large payoffs, we think they will be willing to change.

The second line of defense is more traditional Corps programs -- adaptation and response. Adaptation and response attempts to reduce the adverse impacts on identifiable populations at the time those impacts are expected to occur, primarily through the construction of structures which will minimize the damages caused by change.

Our research program is directed in part to addressing how we might have a more effective long-run adaptation strategy. As part of our risk and uncertainty analysis, we have recently spent a good deal of effort defining the boundaries of those extremes and how society adapts. We also have been pursuing research and technical analysis related to the Great Lakes, sea-level rise, and shoreline protection. The Corps Hydrologic Engineering Center, Coastal Engineering Research Board, Waterways Experiment Station, and Institute for Water Resources all have been working to see how climate change and changes in climate variability will affect Corps programs and operations.

I believe that the Corps should not place a greater emphasis on the adaptation and response line of defense until we have given our economic and political institutions the opportunity to respond systematically. We need a better idea of what the future will look like, on a region-specific basis, and for both climatic and non-climatic variables. Otherwise, our chances of doing the wrong thing, or imposing unnecessary costs upon society, would be too great, and this is a chance that we can't afford.

Nevertheless, the Corps is closely monitoring the debate on climate change and its consequences. It is investing research and study funds on the issue of climate change and its manifestations. As the specifics of climate change and associated change in hydrologic regimes become more understood, the Corps is preparing technical responses that will be available if the resiliency of existing physical, institutional, and economic systems prove inadequate.

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Dr. Robert N. Stearns, of the Policy, Review, and Initiatives Divison of the Headquarters, Corps of Engineers, and Mr. Mark W. Mugler, Mr. Eugene Z. Stakhiv, and Ms. Hanna J. Cortner, of the Institute for Water Resources, assisted in the development of these remarks.

Water Resources Planning Under Climate Uncertainty

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ABSTRACT

Hydrologic risks and uncertainties related to climate and water resources project planning are dealt with from the perspective of an operating agency and its relevant missions, responsibilities and constraints. Although the prognosis that climate changes are likely to occur from CO_2 - induced warming is accepted by Corps scientists and engineers, this knowledge can not be directly factored into planning and design procedures at the present time. There are several indirect paths however, through which likely climate change consequences are implicitly taken into account in planning and design.

In addition, there are realistic expectations that a substantial social adaptation would occur to further ameliorate some of the emerging adverse consequences. The Corps' typical planning horizon is for a fifty year project life. Thus the Corps should be cognizant of significant expected changes in that time frame. However, certain economic decision rules and a fiscal discount rate truncate project evaluation and decision making to about 12 years. On the other hand, the Corps' pragmatic engineering approach to project design relies on historical weather extremes and runoff that has fluctuated from the cold epoch of the late 19th century to a very dry and warm period in the 1930's and 1940's. Together, these two fundamental decision criteria (hydrology and economics) have resulted in projects that are both economically efficient and that are robust and resilient in their performance under reasonably foreseeable climate uncertainty.

The Corps-developed water resources infrastructure, along with that of other federal and publicly owned water agencies, constitutes an immense system that allows for a substantial degree of operating flexibility in many, but not all the river basins of the coterminous United States. Improved management of this system, reallocation of water supply, greater marketing of water rights will provide many areas in the U.S. a valuable margin of safety, during the time in which we strive to better understand the precise nature of climate-hydrology interactions. The Corps is taking steps to address the changes in several separate but ultimately converging research and study efforts, especially to tie risk and engineering

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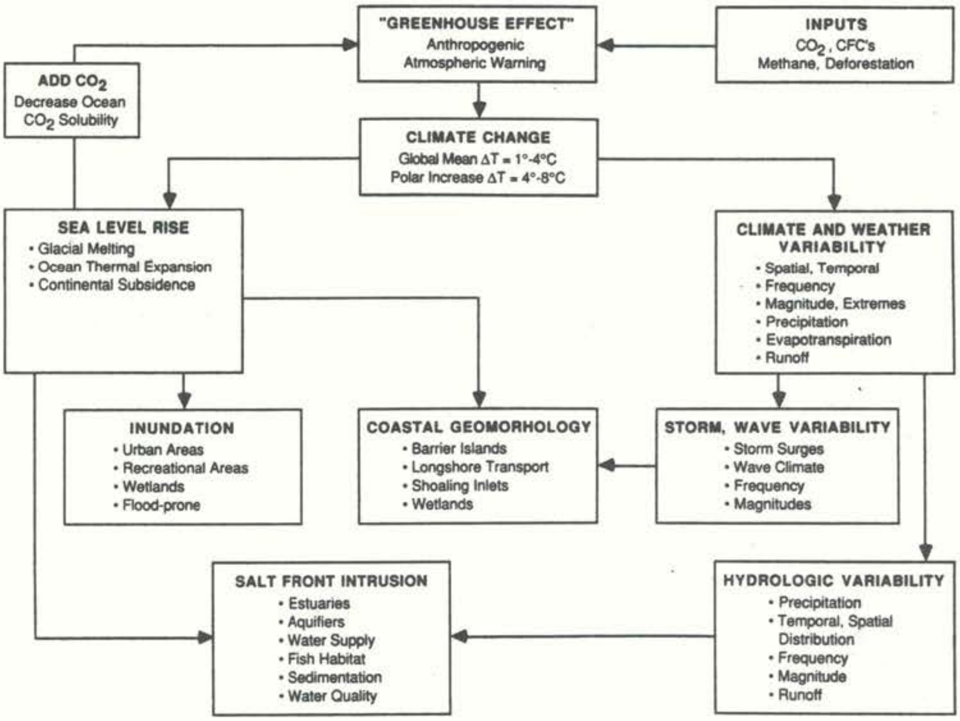
reliability analysis with benefit cost analysis. Risk and uncertainty analysis in project planning will encompass climate uncertainty and its effect on the choices of alternative solutions and their proper scale. More effort will go into the development of hydrologic tools and procedures for dealing with climate uncertainty.

INTRODUCTION

The U.S. Army Corps of Engineers, is responsible for various aspects of a diverse water resources and coastal shoreline protection program. The Corps recognizes that their activities are likely to be affected by the hydrologic, meteorologic, and oceanographic consequences of global warming and expected climate changes (Figure 1). While the Corps may appear to be relatively unresponsive to are increasingly important hazard, it has been delving into the ramifications of these changes for some time now. Most of the Corps' incremental modifications so far have dealt with its planning and design procedures which address the manner in which the Corps computes physical (hydrologic and hydraulic) changes and forecasts economic conditions. A primary change has been in the explicit introduction of risk analysis for the selection of an appropriate design basis for the various alternative plans and corrponent projects whose purposes are to ameliorate hydrologic extremes and mitigate their social and economic consequences.

FIGURE 1

PHYSICAL CONSEQUENCES OF CLIMATE CHANGE



Currently, the Corps is focusing on the relatively uncertain intra-continental effects of climate change on water resources projects. It is recognized that coastal effects, being more certain (at least in the direction of change, if not magnitude) will allow earlier direct response by the Corps and other responsible institutions. It is also recognized that innovative management of existing projects is as important as planning for new projects, perhaps more so because fewer large scale new multipurpose projects are likely to be built in the future. Finally, construction of structural modifications alone is not the only answer. A more complete discussion, beyond the scope of this paper, requires explicit recognition of strategies to prevent or slow the factors that contribute to climate change(e.g. production of carbon dioxide and chlorofluorocarbons); prevent damages from climate change by limiting damageable development or use of resources likely to become scarce; and, for compensation of lost property or abandonment of threatened property (e.g. floodplains, barrier beaches.)

As yet, the Corps has not developed a focused and direct policy statement that emphasizes the importance of considering climate change either for existing water resources management projects or for the planning and design of new ones. Part of the reason resides in the comforting notion that many of the engineering profession's design criteria are already based on meteorologic and hydrologic extremes that are continuously being revised (generally upwards, towards more extreme events) as new data are recorded. This has been the case with the National Weather Services' periodic upward revisions of the Probable Maximum Precipitation (PMP) that, in turn, engenders updates of the design floods for flood control structures. Thus, a case can be made that a good deal of the anticipated climatic variability for the near-term has already been taken into account for existing projects through the Corp's traditional, but highly reductionist and incremental approach to reliability analysis.

Another reason for the absence of a clear policy is that the Corps is reluctant and indeed, unable to use the relatively unrefined climate change predictions (especially on an intra-continental regional basis) as a justification for changing project design features or adjusting design standards. Furthermore, the Corps faces substantial difficulties in explaining and supporting those future probable events that comprise a climate change scenario as part of the series of forecasting activities that serve as the fundamental basis for evaluating alternative projects before a skeptical public influenced by stringent budgetary constraints. It may seem ironic that the very procedures which call for generating future scenarios and forecasts of population, economic growth, land use and ecological trends, often generate the most public controversy in water resources planning. The development of future scenarios called for by the U.S. Water Resources Councils' "Principles and Guidelines" (P&G; 1983), often hold the key to whether a water project is economically justified, as well as how large it should be.

Finally, a policy directed at anticipating changes of fifty years or more from now must take into account the reality of the effect that economic decision rules have on public investment choices. Although the Corps generally plans for a fifty year project life, the effective economic return on a water resources project is heavily influenced by the discount rate. The federal discount rate for water project economic analysis is nearly 9 percent, and is fixed by law. This means that most project benefits are realized within ten years, and the Corps' effective project evaluation and decision horizon is less then fifteen years.

In summary, global climate change implications for quantifying meteorologic and consequent hydrologic changes have not been developed well enough for use by practicing water resources engineers. The Corps of Engineers, as a consequence, is not in a position yet to develop a unified response to the threat of climate change and its water resources management implications. Nevertheless, the Corps has undertaken a series of changes and modest initiatives to some of the more important component parts of its planning, design and management responsibilities. First, both planning procedures and environmental impact statement guidelines call for the consideration of reasonably foreseeable future events as part of developing forecasting scenarios. Second, planning procedures require the development of alternative solutions to water resource problems that fulfill the forecasted needs in an economically efficient manner. The alternative solutions that are typically proposed consist of structural and nonstructural measures. These alternative measures undergo risk-cost analysis that could explicitly consider impacts of climatic uncertainty, both for magnitude and frequency of the hazard and for project benefits and costs. Non-structural measures include emergency warning and evacuation plans, water conservation measures, reallocation of water, trading and selling water rights, floodplain management and other non-traditional solutions.

Design standards also undergo risk analysis as part of structural project performance reliability analysis. Management of existing water resources projects calls for a systems analysis approach and changes in operating rules, supplemented decision-making drifts towards real-time operation. Traditionally the emphasis of Corps concerns has been on the high flow, flood control end of the hydrologic spectrum. Nevertheless, Corps flood control reservoir projects also provide a capability for dealing with low flows, increasing the robustness and resiliency of the entire operating system. These systemic properties should continue to be exploited as future demands shift under climate uncertainty, particularly in meeting future urban water needs.

PREVIOUS WORK

One can argue that the Corps has contended with the climate variability hypothesis, and its consequences, both in water resources management and in coastal shoreline protection since its assumption of those responsibilities. "Normal" low frequency and high frequency climate variability, without the superimposed consequences of global warming, have served as the basis for most project design. Some of the nation's best theoreticians helped the Corps develop and continually refine its current procedures and practices for design under climate uncertainty. For example, P. Bruun, who is often cited for his perceptive thinking on the coastal geomorphic consequences of sea level rise did some of his earliest work for the U.S. Army Corps of Engineers Beach Erosion Board in the mid-

1950's. Likewise, some of the earliest applications of stochastic hydrology and watershed modeling were performed under research initiated by the Corps of Engineers, the Soil Conservation Service, and the Bureau of Reclamation. The work of the Corps' Hydrologic Engineering Center (HEC) is known worldwide. The Corps' Institute for Water Resources (IWR) initiated a series of studies on climate change that paralleled an increased interest in global warming and its hydrologic consequences as part of the National Climate Program Act of 1978. IWR commissioned a series of studies to ascertain the hydrologic and geomorphologic impacts of climate change under four scenarios:

I	$+2^{\circ}$C, +10% precipitation
II	$+2^{\circ}$C, -10% precipitation
III	-2°C, +10% precipitation
IV	-2°C, -10% precipitation

Stockton and Boggess (1979) produced a comprehensive review of the hydrologic implications on each of the 18 hydrologic basins of the basins of the coterminous United States. Knox (1979) reviewed the possible geomorphologic consequences on each of the 18 river basins as well. Beard and Maristany (1979) discussed the potential changes from the vantage point of water resources engineering practices, while Fritts and Lofgren (1979) placed climate change scenarios within the context of periodic shifts in climate patterns during the pst 300 years based on tree rings studies.

ENGINEERING RISK AND RELIABILITY ANALYSIS

There have been other studies on the same theme, using different approaches and a variety of sophisticated models that are very well summarized by V. Klemes (1985) and M. Beran (1986). The key point is that the Corps and other operating water resources agencies have been aware of the scientific progress in climate change modeling and about the debate that has ensued with respect to the likelihood of predicted outcomes. The Corps is also aware that many authors that have written on the climate-hydrologic linkages have lamented the fact that the necessary transformations between Global Circulation Models (GCM's) that are time - and space - averaged and the consequent climate and weather effects, that are prerequisites for better hydrologic prediction, are seriously lacking. As a consequence, hydrologists have had to work backwards in evaluating climate change consequences by constructing a set of plausible scenarios, based on GCM results without even being able to assign a reasonable set of probabilities to those scenarios. Thus, while global warming should, on a global scale, lead to a "warmer-drier" scenario, it is not at all certain that some areas of the North American continent will not be "cooler and wetter". We also do not know whether the variability of the extremes will increase or decrease, notwithstanding the Environmental Protection Agency's (1984) attempt to transpose global changes to regional runoff changes.

The absence of good information on consequences is especially troublesome for an operating agency such as the Corps that interacts closely with the public. The Corps plans and designs water resources management projects under intense public scrutiny and thus is held accountable for a large number of forecasting assumptions, among which include the selection of extreme events as design objectives, and of future water demands and of population growth. While other regulatory agencies and scientific organizations propose various conditions, regulations and constraints on a range of future human activities, the Corps must continuously justify them in terms of social acceptability, economic efficiency, financial feasibility, and engineering reliability at the project level.

This continuous public pressure has contributed to the development, over the course of 50 years of application and refinement, of a large body of empirical and theoretical procedures and decision rules that have yielded what are generally considered to be fairly robust and resilient project designs. The empirical design procedures are intrinsically related to climate variability. We think that this empirical approach, emphasizing as it does the extremes of climate variability over the past 100 years, encompasses a significant proportion of the <u>anticipated</u> changes, at least for large scale water management systems.

Fiering (1982) defined <u>robustness</u> as the sensitivity of key system design parameters to variability in future events. That is, a robust water resources system is able to absorb the inevitable range of uncertainties associated with the planning and design of a water resources management project. These include the typically cascading or cumulative uncertainties of model selection, parameters and data and what is sometimes termed "<u>strategic</u>" uncertainty - i.e., the forecasts of future conditions, needs and projects outputs. <u>Resiliency</u> is defined as the ability of a system to return quickly to its designed performance levels, even after failure (Fiering, 1976).

What makes the Corps confident that their current water management systems can absorb the anticipated near-term climate changes? Many of the Corps' critics contend that Corps projects are overdesigned. In some cases that is probably true. The Corps was trying to anticipate future needs without a firm basis in growth projections. In most instances, however, the design criteria merely reflected the conventional engineering approach of focusing on an extreme event or condition, e.g., the critical drought period of record or the probable maximum flood or hurricane. This approach accounted for the unknown climate variability and the uncertainty that the existing data did not reflect the true range of possible events.

As a counterweight, however, the Corps' complex economic efficiency-based evaluation rules that are superimposed over conventional engineering design procedures, drive both project selection and sizing towards an optimum in terms of the appropriate or efficient level of protection. For example, a flood control reservoir is first sized for the economically efficient level of flood protection, generally between a 100-year flood and a larger Standard Project Flood (SPF). But the dam spillway is sized separately for an even more extreme flood event, termed the Probable Maximum Flood (PMF) to prevent dam failure through overtopping. Each analysis undergoes a separate risk-cost evaluation, operating under different economic decision rules, to reflect the escalation in the consequences of failure from property losses to loss of life. Similarly, an levees have "freeboard" that compensate for uncertainty inherent extreme flood events. There have been many recorded instances in which dam spillways and levee freeboards have saved the populace from severe, unanticipated flooding events.

Matalas and Fiering (1977) concluded, and subsequently reinforced in a number of other papers on the subject, that "...it is comforting to recognize that most large systems contain so much buffering and redundancy that resilient design can be operationally achieved without resort to sophisticated or elaborate projections about the climate". Several other comparative studies have shown that there is little discernible statistical difference in hydrologic models that reflect a stationary climate hypothesis versus those of a non-stationary climate, at least for long-term changes of the mean in precipitation and runoff of less than 20% (Klemes, 1985). Thus, public water resources agencies have effectively been conducting the design of large hydraulic structures and water control systems almost as if anticipating climate change. The design of smaller structures, such as urban drainage culverts and sewers, and local flood protection projects are more susceptible to changes in the variability of events, however.

RISK-COST EFFECTIVENESS ANALYSIS

Society cannot afford to build "<u>fail-safe</u>" projects anymore. It isn't economically efficient, either for water supply, flood control, or hurricane storm protection on coastal shorelines. Notwithstanding the Corps' past history of a reliability-based analysis for extreme events, their design concept has increasingly become "<u>safe-fail</u>". It is a strategy of designing flood protection for less than the extreme event of record. A structural measure (levee, channel) is complemented by emergency management plans that mitigate the damages of designed (i.e. safe-fill) failure of structural solutions. In other words local flood protection could conceivably be designed for a 20 to 50 year level of protection, as long as there is a complementary flood warning and evacuation plan. These complementary mechanisms represent an important contributing factor to the robustness and resiliency of water resources management systems, and are specially relevant to adaptation under climate uncertainty. The dichotomy between structural and non-structural measures also serves to emphasize functional and conceptual differences between risk assessment and prediction of climate consequences from that of risk management. While hydrologists may not be able to explicitly factor in the anticipated variability of climate change, especially if they rely on empirical rather than causal models, water resources planners and engineers can implement a wide range of management measures that increase the robustness and resiliency of solutions that can operate under an anticipated range of climate uncertainty. Adaptive risk management includes measures for floods and droughts.

Among the measures that are actively considered by water resources planners (including engineers, economists, social and environmental scientists) are the previously mentioned hazard mitigation measures that are employed when the hazard prevention measures (dams, levees, sea walls) fail. Also, many solutions address longer term and more permanent adjustments in the way which society uses its water resources. Changes in water pricing will redistribute the demand toward more efficient uses of water and will induce the various sectors (e.g., agriculture, municipal and industrial) to develop more efficient water using methods. Water can also be reallocated by changes in water laws and reservoir operating criteria. Water resources management is becoming more efficient and effective, with greater reliance on a range of water conservation measures and a systemic water resources operations approach. All these changes increase the buffering capacity of the existing systems, i.e., its robustness (ability to absorb surprises) and resiliency (ability to recover from failure).

ANTICIPATED WATER RESOURCES PROBLEMS

Notwithstanding this admittedly benign assessment of the near-term (10-20 years) ability of a regional water resources infrastructure to absorb most consequences of anticipated climate uncertainty, there are many user-specific and site-specific water resources needs that are currently stressed and where substantial shortfalls already exist. Little has been said also about the possible effects of climatic marginality (Wigley, 1985). This is the physical reality that under a climate change scenario, i.e. a shift in the mean, would also be accompanied by extreme events that may occur more frequently and where the frequency might change substantially even from a rather small change in the mean. Areas that are currently in marginally productive agricultural zones, would be most affected by the amplified cumulative impact of successive extremes (Wigley, 1985).

The Corp's (Stockton and Boggers, 1979) study of the sensitivity of 18 river basins to climate change focused on water shortages rather than on floods. Stockton's work showed that even today, several river basins are operating near the upper limit of their potential yield (Table 1).

TABLE 1

	Present Climatic State					Scenario 1 (warmer and drier)			Scenario 2 (cooler and wetter)		
Region	Estimated mean annual supply (bgd)[a]	Estimated mean annual requirement (bgd)[c]	requirement / supply	total storage / mean annual flow	Q_{05}/Q_{95} (streamflow)	Estimated mean annual supply (bgd)	total storage / mean annual flow	requirement[e] / supply	Estimated mean annual supply (bgd)	total storage / mean annual flow	requirement / supply
01. New England	78.6	1.03	0.01	0.38	2.2	56.6	0.54	0.02	108.5	0.28	0.009
02. Mid-Atlantic	81.0	3.54	0.04	0.48	2.4	53.5	0.73	0.07	115.0	0.34	0.03
03. South Atlantic Gulf	232.5	10.05	0.04	0.39	2.9	148.8	0.42	0.07	339.5	0.19	0.03
04. Great Lakes	75.3	4.69	0.06	0.27	2.3	50.5	0.41	0.09	103.2	0.20	0.04
05. Ohio	179.0[b]	4.33	0.02	0.29	2.4	111.0	0.47	0.04	256.0	0.21	0.02
06. Tennessee	41.1	1.11	0.03	0.75	1.9	25.9	1.20	0.04	56.7	0.55	0.02
07. Upper Mississippi	114.0[b]	2.66	0.02	0.27	2.9	70.7	0.51	0.04	166.4	0.18	0.02
08. Lower Mississippi	416.8[b]	5.51	0.01	0.05	3.7	291.8	0.09	0.02	571.0	0.03	0.009
09. Souris-Red-Rainy	6.1	0.47	0.07	1.72	1.4	3.4	3.11	0.14	10.2	1.03	0.05
10. Missouri	61.5	26.14	0.42	2.92	4.1	22.1	8.12	1.18	100.9	1.77	0.26
11. Arkansas-White-Red	67.7	12.03	0.18	1.32	5.5	31.1	2.41	0.39	138.8	0.66	0.09
12. Texas-Gulf	35.6	12.52	0.34	1.97	10.3	17.8	3.94	0.70	71.2	1.05	0.18
13. Rio Grande	5.3	4.80	0.87	3.58	22.0	1.3	14.2	3.69	9.5	1.99	0.51
14. Upper Colorado	13.9	11.75[d]	0.84	1.38	4.0	9.3	2.21	1.26	27.0	0.72	0.44
15. Lower Colorado	8.3[b]	9.87	1.18	12.66	1.4	3.6	18.99	2.74	14.1	4.83	0.70
16. Great Basin	13.9	4.37	0.31	0.51	3.8	7.6	0.93	0.57	25.3	0.29	0.17
17. Pacific Northwest	286.5	17.28	0.06	0.40	1.9	171.8	0.62	0.10	386.6	0.28	0.04
18. California	73.4	30.39	0.42	1.08	4.0	41.1	2.15	0.74	119.6	0.63	0.25

(a) assumes zero ground water overdraft
(b) inflow from upstream region included
(c) projected through the year 2000
(d) includes 6.70 bgd for downstream obligations
(e) assumes no increase in evapotranspiration rate from present climatic state

A warmer and drier climate scenario, which is the most likely for these arid areas, well only exacerbate the problems. Yet, flooding is still the most destructive and costly of natural disasters in the United States, accounting for average annual damages of $4.0 billion and nearly 250 fatalities (Schilling et. al, 1987). There are approximately 20,000 communities that have invested in some form of flood control or storm drainage systems. Unlike the redundancy built into the large scale mainstream water control structures, storm drainage systems are designed for more modest sized events, usually for storms between a 5-25 year recurrence.

Drainage, or stormwater management, is a companion to flood control, emphasizing the rapid removal of excess water. The cumulative investment in urban stormwater drainage is thought to exceed that of flood control projects according to a report on water resources by the National Council on Public Works Improvement (Schilling, et. al, 1987). In addition, the Public Works Improvement Council report provided an estimate of an additional investment of more than $100 billion that would be needed for constructing and rehabilitating combined stormwater sewers. The sizing of those facilities is very sensitive to storm frequency, seasonal distribution, and volume estimates. Thus, climate change impacts for this feature alone could have significant financial consequences, in addition to introducing considerable uncertainty into design reliability.

Because there is no clear picture of how the temporal and spatially-averaged global warming outcomes of the GCM models will affect continental and regional weather patterns, it is difficult for hydrologists to conduct direct sensitivity analysis on the hydrologic uncertainty. The present climatic-hydrologic uncertainty is not only one of magnitude, frequency, and variability, but also of direction. A "warmer-drier" scenario may well be the most likely consequence in the Midwest, forcing water resources planners to focus on drought and water supply shortages. Simultaneously, there may be "cooler-wetter" conditions in the Pacific northwest and southeastern United States, requiring a reevaluation of our flood-related design criteria, especially for the extensive levee-confined river reaches of the lower Mississippi valley.

CHANGES IN EVALUATION PROCEDURES AND ADAPTIVE MEASURES

A concerted effort needs to be made by academia and the Federal research laboratories dealing with hydrologic and hydraulic phenomena to provide information and techniques that are useful to engineering practitioners. Too much research in hydrology has been diverted to marginally relevant statistical and probabilistic empirical formulations that do not further the understanding of the underlying phenomena and their consequences. There is a serious debate within the hydrologic research community about the value of much of the research that is produced (e.g., Fiering, 1982; Klemes, 1986; Beran, 1986). This questioning of purpose has carried over into the even more complex area of hydrologic analysis under climate uncertainty.

The more pragmatic operating agency hydrologists would just as soon sit back and wait for the controversies to resolve themselves and for climate modelers to provide more site-specific and accurate information on precipitation magnitude and variability. The National Weather Service should play a major role in the transformation of global climate data to regional precipitation information. The sizing of water supply and flood control structures depends very much on the timing and distribution of runoff - whether it comes in a single season or as a double seasonal peak; whether the precipitation is monsoonal or evenly distributed; whether it comes as snowmelt or as storms. This is the level of information that the hydrologist needs from the climate modeler. We also need to begin using some of the better developed phenomenological or "causal" watershed models to better understand the sensitivity of various river basins to climate change. Some work along these areas has already been done (Klemes, 1986; Gleick, 1987). Curve-fitting alone will not do the job as we began to prepare for the consequences of climate change twenty or more years from now.

We also need a complementary review of water resources evaluation principles and procedures. A formal and uniformly structured approach to risk analysis would comprise one set of evaluation principles that would assist in decisionmaking under uncertainty. Formulation of alternative solutions that are more robust and resilient would be one of the desired outcomes of risk sensitivity analysis. However, these solutions are often "second best" in terms of economic efficiency criteria, so explicit risk-cost tradeoffs must be allowed to become part of the water resources evaluation procedures, rather than a strict adherence to the maximization of net benefits criterion as directed in the "Principles and Guidelines" for water resources planning and evaluation. This is true both for beach protection projects, that are under the double threat of sea level rise and variability of extreme events, as well as for water resources management systems.

More effort must be put into the prevention of the causes of climate change. This is a man-made phenomenon that can be controlled to some extent in a fairly cost-effective manner. A good start has been made by the recent international treaty on the control of the causes of ozone depletion. There is an inertia in the atmosphere-ocean system that will, in any event, still drive the specific climate-weather adjustments to significantly affect weather variability and the extremes of floods and droughts for some time to come, even after complete control of the agents of warming.

If little can be done to reduce or decelerate the causes of climate change, then society will have to consider larger structural changes, depending on how severe the climate-induced water resources consequences will be. We may have to consider relocating large segments of the population from the flood plains, coastal areas, and arid areas. A large scale economic adjustment will likely take place both in the composition of agricultural products and in the geographic distribution of agricultural areas. This will put additional, and possibly severe pressure on the dwindling natural ecological resources, particularly the prairie pothole wetlands and bottomland hardwood forests of the lower Mississippi valley. Winter navigation in the Great Lakes and many of the major rivers would be affected, possibly increasing costs of transporting goods, either because the waterways would be: frozen over longer periods; in flood stage more frequently; in low flow stages that constrain navigability.

Certainly more effort needs to be invested in climate modeling and the quantification of the climate-meteorology-hydrology linkages. Special attention should be given to the anticipated joint phenomeua of increased weather variability; greater frequency of extremes; and the potentially disastrous consequences of successive extremes. This is, perhaps more critical for droughts, as urban areas have grown rapidly in the past two decades, and depend on fairly rapidly exhaustible water supply sources. Drought planning and management is an important complementary action towards a complete risk management approach under climate uncertainty.

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CLIMATE CHANGE AND NORTH AMERICAN AGRICULTURE PANEL

INTRODUCTION

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Climate has a significant impact on agricultural productivity and geographic distribution of crops. Examples of some negative impacts of climate on crops include the persistent Great Plains drought between 1932 and 1937, which contributed to nearly 200,000 farm bankruptcies and the recent drought in 1983, which contributed to an almost 30% reduction in corn yields in the United States. The climate variations in precipitation which produced these effects are small in comparison to the temperature increases predicted due to increased trace gases.

Now climate modelers are predicting temperature increases by early in the next century of well above any level experienced in the past 100,000 years. Modelers are less certain about what may happen to precipitation, a key agricultural variable. While precipitation is likely to increase globally, since a warmer atmosphere can hold more water vapor, local changes in precipitation may be either positive or negative. Some climate models predict summer dryness in mid-continental regions; in the case of the United States and Canada, this would affect the heartland of agricultural production.

We have gathered here today a distinguished group of scholars who have begun to study what the possible effects of changing climate may be on agriculture. We are most fortunate in having two Canadian scientists on the panel, because our Canadian colleagues have been in the forefront of research on climate change and agriculture. Canadian agriculture may benefit from the predicted warmer winters and longer growing seasons at higher latitudes, to the extent that hydrologic regimes and soil resources allow.

Today's panel also makes an important point about how we study what may occur in the agricultural sector as climate changes. We need scientists from many fields — agronomy, agricultural meteorology, and economics (among others) — to participate in climate change research because agriculture has numerous overlapping spheres. It is not enough to study the effect of climate change or increasing CO_2 on crop yield alone, the traditional variable of agricultural interest. Rather, attention must be paid to determining where the agricultural system is robust and where it is vulnerable.

Overlapping spheres in the agricultural system which must be considered include crop yield responses to climatic variables and increased CO_2, crop-pest interactions, farm-level decisions, regional and international markets, and the effects of a changing agriculture on the environment.

Research on crop growth and climate change has often addressed climatic and vegetational effects of increasing CO_2 separately, even though biological and atmospheric processes are linked in many ways and may have synergistic effects. Many studies on CO_2 and agricultural crops in field chambers have shown positive direct effects of increased CO_2: enhancement of photosynthesis and water-use efficiency. These beneficial results must be weighed in relation to the magnitudes of the climatic changes predicted by the climate models in order to more completely understand the nature and direction of physical crop responses.

How climate change affects agriculture also depends on what each individual farmer or farm business decides in the face of changing climatic variability, particularly changes in climatic extremes. These decisions involve aspects such as cropping systems, irrigation regimes, and ultimately the success or failure of each individual farm. The aggregated decisions of all individual farmers affect agricultural infrastructure on regional scales, in such areas as tractor dealerships, irrigation water management, regional markets, and shipping patterns.

The future of U.S. agriculture also depends greatly on what national farm policy is promulgated each year here in Washington, D.C. Should the potential for climate change affect this policy-making process? And what about possible adjustments to risk programs and water quality regulations?

Moving beyond national and continental boundaries, how climate change may affect American agriculture depends to a large extent on what happens in other parts of the world. Which areas of the world may benefit from climate change and which may be hurt? International vulnerability may create markets for North American grain, while beneficial effects may limit those markets. Issues of world food supply, grain surplus and redistribution should also be considered.

Last but not least, we must consider the interactive relationships of changing climate, agriculture and the environment. As a result of the potential climatic changes and the reverberating effects throughout the agricultural system, agricultural zones may shift around the continent. Besides the effects of such regional shifts on human communities, we must seek to understand the consequences to the environment. We must ask, "What may happen to soil erosion?" What may happen to the fate of agricultural chemicals?" What may happen to forests, rivers and wildlife habitats?"

The distinguished members of our panel address some of these many issues in their papers. Methods for studying climate change, increasing CO_2 and agriculture are improving as field techniques and climate, crop growth and agricultural economic models continue to be developed. Biotechnology and other advances may alter the practice of agriculture in some ways as we proceed into the future. The goals of climate change impact research are to define more clearly the ranges of possible impacts and to engender flexibility in society's actions in light of them.

Climate Change - Implications for Agricultural Productivity on the Canadian Prairies

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ABSTRACT

This paper highlights the potential impact of possible climatic change resulting from increased CO_2 warming on prairie agriculture based on work undertaken for spring wheat production in Saskatchewan. Given the climate projections for a doubling of atmospheric CO_2 from the GCM - modeling work at the Goddard Institute for Space Studies the annual temperature and precipitation would be increased by an average of 4.7°C and 15%, respectively. Agricultural implications of this change include: an increase in the average growing season length of 48 days, an advance in the growing season start or planting date of about 2-3 weeks, and an extension of the fall harvest period by about 3-4 weeks. The Prairies would become more drought prone, and total spring wheat production could be reduced by 6 - 28%. A shift to fall sown crops is highly probable to avoid mid-summer drought.

INTRODUCTION

Spring wheat is the most important cereal grain crop in the Prairies and indeed in Canada. It is grown more extensively and produced in greater quantity than any other crop. For example, total harvested area of wheat in the Prairies in 1985 was 11.4 million hectares and total production was 25.5 million tonnes (Mt); Saskatchewan produced 15.0 Mt, Alberta 6.4 Mt and Manitoba 4.1 Mt, respectively (Statistics Canada, 1987). The value of this crop to the Prairie economy in terms of cash receipts was $2.96 billion and exports of this crop contribute significantly to Canada's international balance of trade (Statistics Canada, 1987). Consequently, the global warming currently estimated at 1.5 to 4°C for a doubling of CO_2 (Manabe and Wetherald, 1980; Hansen et al., 1981; Mitchell, 1983; Parry et al, 1987) could have major repercussions for both Prairie agriculture and the Canadian economy in general.

The potential implications of CO_2 climate change for spring wheat in Saskatchewan have recently been outlined in detail by Williams et al. (1987). This study forms part of 6 country cooperative international study sponsored by the International Institute for Applied Systems Analysis in Laxenberg, Austria described in detail by Parry et. al. (1987). In this paper some of the major findings of the Saskatchewan study related to the potential impact of CO_2 climate change on the growing season climate, spring wheat maturation and production are presented. As well, implications for drought and changes in Prairie wheat zonation are discussed briefly.

CLIMATIC WARMING - WHAT DOES IT MEAN FOR THE CANADIAN PRAIRIES?

If the Prairies undergo the projected climatic change suggested by some of the recent GCM experiments how would the new climate compare with the current? In the Saskatchewan study the climate change projections derived from the GCM modeling experiments published by the Goddard Institute for Space Studies (GISS) for a doubling of atmospheric CO_2 concentration (Hansen et al., 1983) were used as the basis for investigating the impact of potential climatic change on spring wheat production. The following discussion attempts to outline some of the changes we might expect should the climate change according to the GISS projections.

The existing growing season climate in the Canadian prairies can be characterized as being short, warm and dry. In Saskatchewan, the growing season length (GSL) varies from 100 to 120 days generally decreasing in a south to north direction (Fig. 1); the growing season start (GSS) varies from May 17-27 and the growing season end (GSE) from September 10-15. Total degree days with a base above 5°C for crop growth ranges from 1100 to 1400 (Fig. 2). The region is dry with total growing season precipitation ranging from approximately 180 mm to 240 mm (Fig. 3) and a ratio of precipitation to potential evapotranspiration ranging from slightly less than 0.35 in the dry southwest to slightly greater than 0.6 in the moister north and eastern areas (Fig. 4).

Table 1 outlines the monthly temperature and precipitation changes projected by the GISS experiments for Saskatchewan. As shown, increases in seasonal temperature vary from an 3.3°C in June and July to 6.3°C in December and January. In total, warming suggested by the GISS model would increase the annual temperature in Saskatchewan by about 4.7°C. As well, annual totals of precipitation are projected to increase by about 15%, and growing season values by 5-15%, respectively.

Figures 1 to 4 outline the change in growing season length, growing season degree days, precipitation received during the growing period and the ratio of precipitation to evapotranspiration. As shown, the effect on the growing season length is an average increase of 48 days, distributed relatively uniformly across the province. The increase in GSL will impact on both the GSS and GSE. The GSS will be advanced an average of 19 days in the spring, while the GSE will be extended by an average of 29 days in the fall. In conjunction with the increase in GSL, the higher temperatures will augment crop growth by about 800 degree days or 60 to 70%. In effect, the projected GISS warming on the climate of Saskatchewan would amount to a shift of the climate typical of Nebraska some 450 km to the south north to Saskatchewan.

VARIATION IN THE GROWING SEASON LENGTH (DAYS) IN SASKATCHEWAN DERIVED FOR THE 1951-80 NORMALS PERIOD AND GISS 2xCO$_2$ SCENARIO

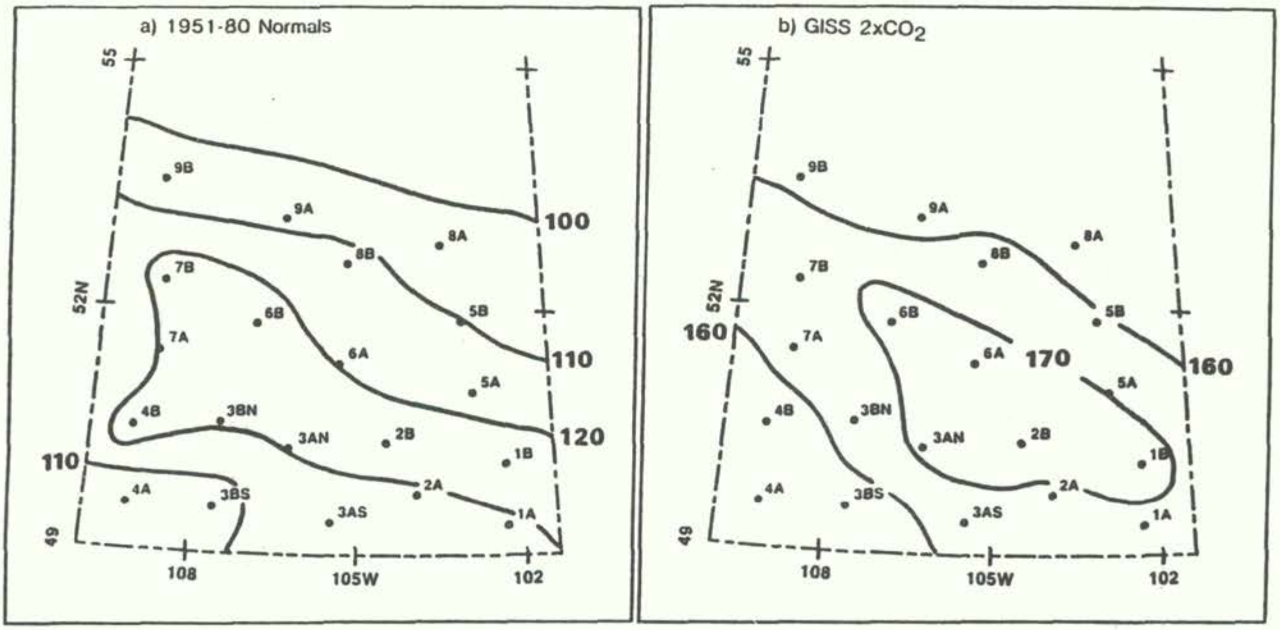


FIG. 2

VARIATION IN GROWING SEASON DEGREE DAY TOTALS GREATER THAN 5°C IN SASKATCHEWAN DERIVED FOR THE 1951-80 NORMAL PERIOD AND GISS 2xCO$_2$ SCENARIO

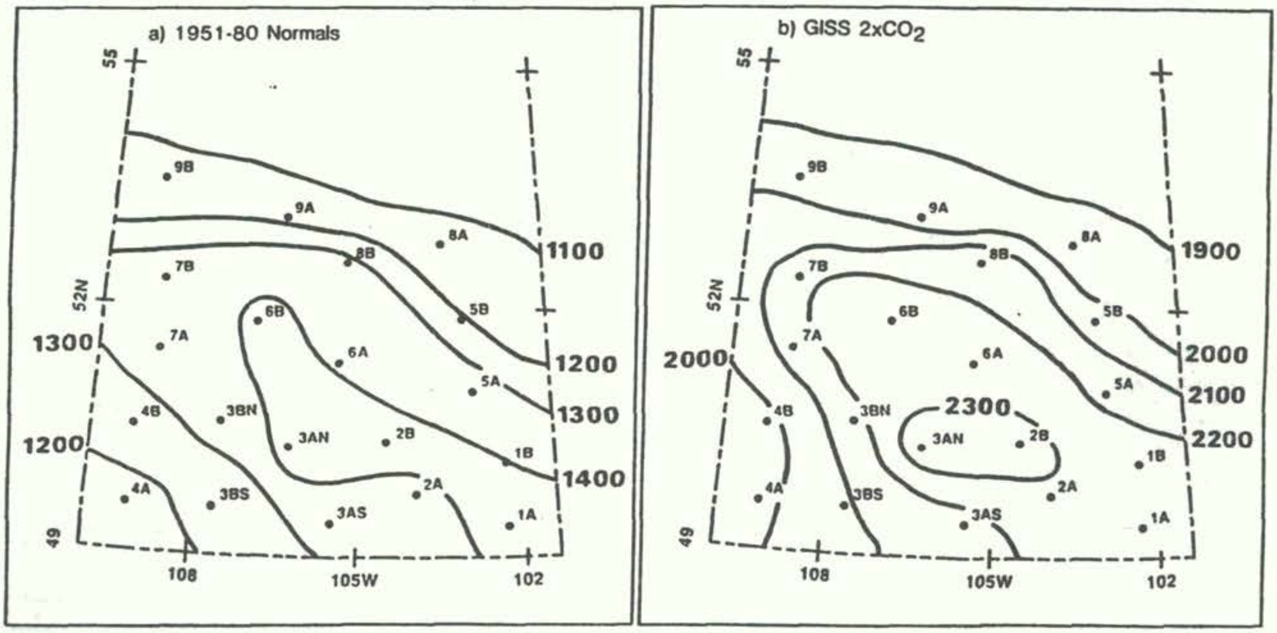
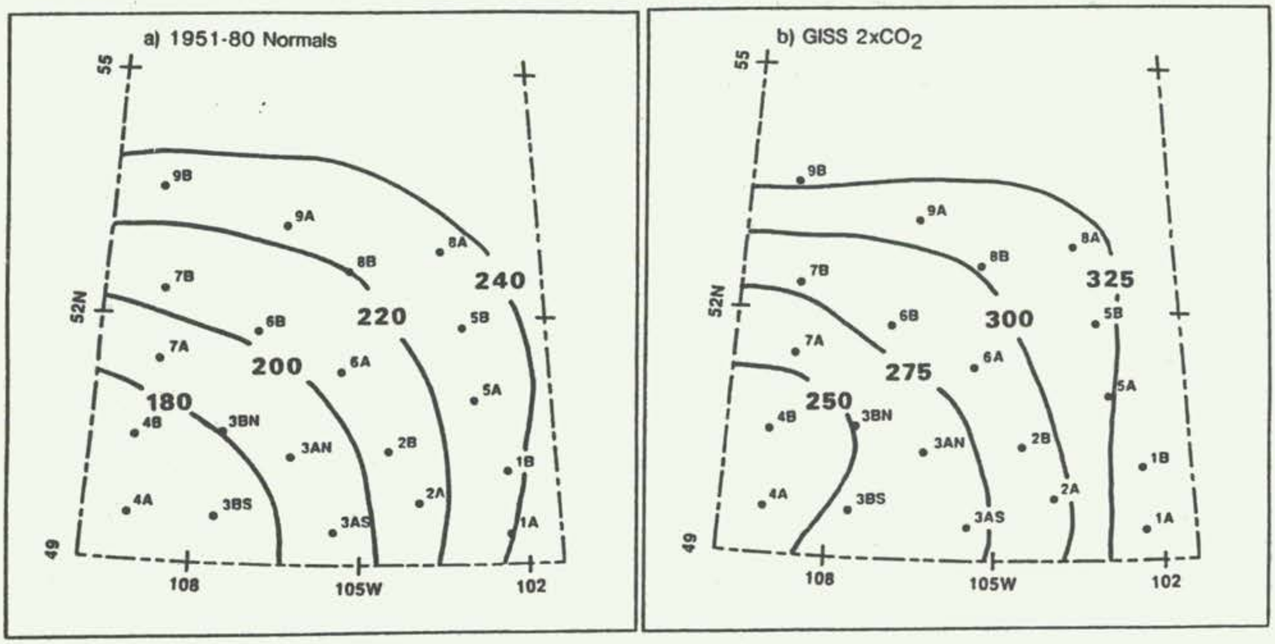


FIG. 3

VARIATION IN GROWING SEASON PRECIPITATION TOTALS (mm) IN SASKATCHEWAN DERIVED FOR THE 1951-80 NORMALS AND GISS $2xCO_2$ SCENARIO

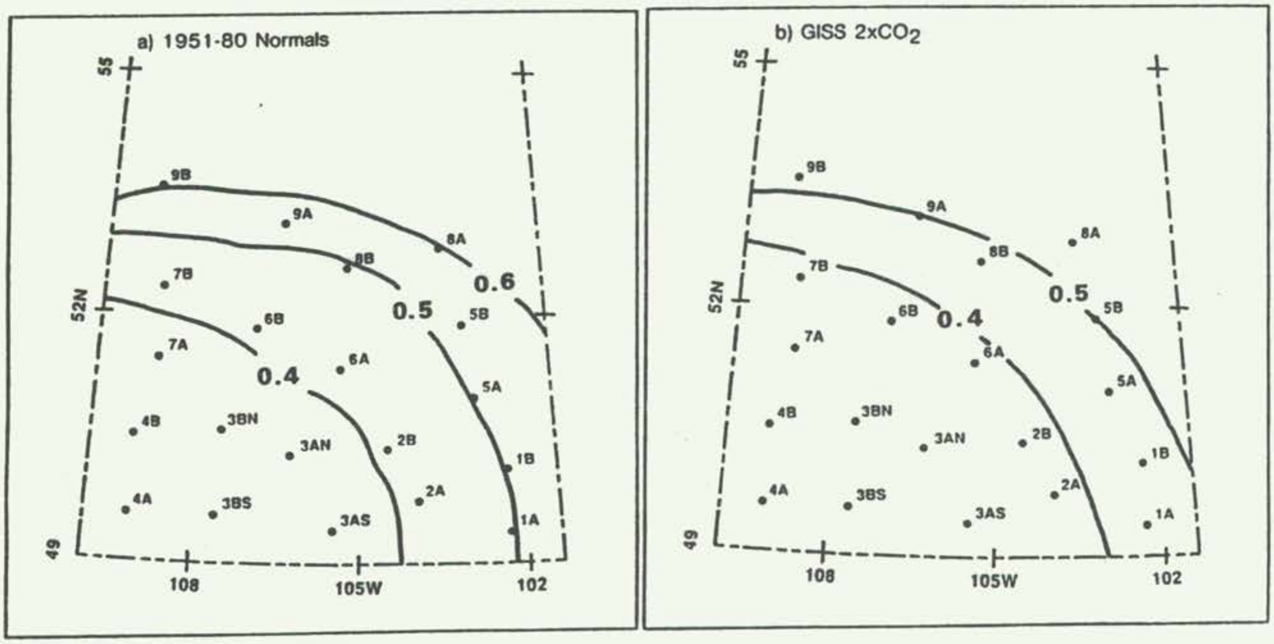


a) 1951-80 Normals

b) GISS $2xCO_2$

FIG. 4

VARIATION IN THE GROWING SEASON RATIO OF PRECIPITATION TO POTENTIAL EVAPOTRANSPIRATION (P/PE) DERIVED FOR THE 1951-80 NORMALS AND GISS $2xCO_2$ SCENARIO



a) 1951-80 Normals

b) GISS $2xCO_2$

Table 1: Average Monthly Temperature and Precipitation Changes Projected for Saskatchewan by the GISS $2xCO_2$ Experiments

	Temperature (°C)	Precipitation (%)
January	6.1	+ 29
February	5.6	+ 34
March	4.8	+ 24
April	4.1	+ 17
May	3.7	+ 15
June	3.3	+ 15
July	3.3	+ 13
August	3.7	+ 5
September	4.6	- 1
October	5.3	+ 12
November	5.9	+ 26
December	6.3	+ 30
AVERAGE	4.7°C	+ 15

Impact on Spring Wheat Production

Given a climate change of the GISS magnitude what sort of impact might we expect to see on spring wheat maturity, yields and production in the Prairies? Currently, the average time required to mature spring wheat in Saskatchewan ranges from 86 to 98 days. The number of days required to reach maturation is closely correlated to the total heat accumulated from the time of planting to the point the crop is ripe (currently 1000-1100 degree days). In general, the key factor affecting wheat development throughout the Canadian Prairies is the rate of heat accumulation (i.e. the hotter it is the faster wheat matures); the areas with the longest maturation time requirement corresponding to the coolest areas. Conversely, the warmer the temperature the faster spring wheat matures.

Maturation requirements for current climatic conditions and for the GISS data are shown in Figures 5a and 5b. As shown, the impact of the projected GISS warming would be a reduction in maturation time for current spring wheat varieties of 4 to 14 days to the 79 to 84 day range. However, unlike the present where the longest requirement for maturation tends to be in the more northern part of the agricultural area, the GISS warming would reverse this pattern: 79-80 days, as opposed to 82 to 84 days in the south and central parts. A further impact of the warming conditions suggeststhat the region would become much more homogeneous. For example, there is a 12 day range in maturation time under current climatic conditions (86-98 days), for GISS the range would decrease to 5 days (79-84 days). Both effects, although temperature induced, are augmented by the advance in the planting date of 2 to 3 weeks and the coincident increase in daylength.

In the Saskatchewan study the impact of the GISS climate change on spring wheat production was undertaken assuming changes in temperature and precipitation only. No direct effects of the increased CO_2 levels on plant photosythetic capacity were considered. In more recent work, detailed by Stewart (1986), the direct affects of elevated CO_2 levels were taken into account. Findings suggest that spring wheat production in the absence of any direct CO_2 effects could be reduced by 18% if the projected GISS precipitation were received and by 28% if precipitation remained at current levels. Taking into consideration a possible 15% increase in photosynthetic capacity, analysis of the data revealed that spring wheat production would still decrease by 6-14%. Overall, the implications of the crop modelling experiments given a warming of the magnitude projected by GISS suggest that: precipitation will have to increase significantly more than the 15% projected inorder to maintain production at current levels, otherwise production would be sharply reduced; a 20-25% increase in photosynthetic capacity would be needed to overcome the projected temperature and moisture effects; if the precipitation decreased below current levels this figure would increase significantly; yield and production decreases would be greater in the northern agricultural areas, and; yields and production throughout Saskatchewan would be more homogeneous.

Implications for Drought

Model results reported in this paper suggest that the Canadian Prairies would be only slightly drier and that the overall impact from a doubling of CO_2 would be a decrease in spring wheat production ranging from 6 to 26%. However, the question one might ask is what effects this climate change would have on the frequency and severity of drought events. The last 5 years clearly illustrate the impact that drought can have on agricultural production and the economy. For example, drought in 1984/85 cost the Prairie economy an estimated $859M in lost production, increased feed costs and destocking of beef cattle (Tung, 1986). Given the magnitude of this loss it is quite apparent that the stability of Prairie agriculture could be severly altered shaken if drought frequency and severity were to increase.

Results of a drought analysis in the Saskatchewan study (Williams et al. 1987) using the well known Palmer Drought Index (Palmer, 1965) suggest that the GISS warming would in fact lead to a more drought prone climate, primarily due to increased evapotranspiration associated with elevated temperatures. More specifically, the frequency of drought months would be increased by a factor of 3 to 10, drought duration would be longer and more severe, and that the return period of drought and severe drought events would be halved (Table 2). Implications of these findings suggest that the relatively minor long term yield changes described earlier could be somewhat of an over-simplification. Indications are that if the climate warms as projected by GISS, fluctuations in annual yield could be quite significant as drought years becoming more frequent and more severe.

Given this, the current spring wheat cropping system would certainly be pushed to the limit in terms of the farmers' ability to cope financially with good and bad years. As the financial stress increases the logical course of action would be a shift to crops that will reduce the strain.

Table 2: Change in Drought Potential For Saskatchewan Based on Palmer Drought Index Analyses

	Frequencies			Return period(years)	
	PERIOD (1950-82)	GISS1	GISS2	PERIOD (1950-82)	GISS1
Severe Drought	0.3%	0.9%	10.8%	15 to 35	8.5 to 17.5
Drought	3.0%	9.1%	39.6%	6.5 to 10	4 to 6

From Williams, et al. (1987)

GISS1 - Temperature and precipitation
GISS2 - Temperature only; precipitation held constant at 1951-80 level

Shifting Crop Boundaries

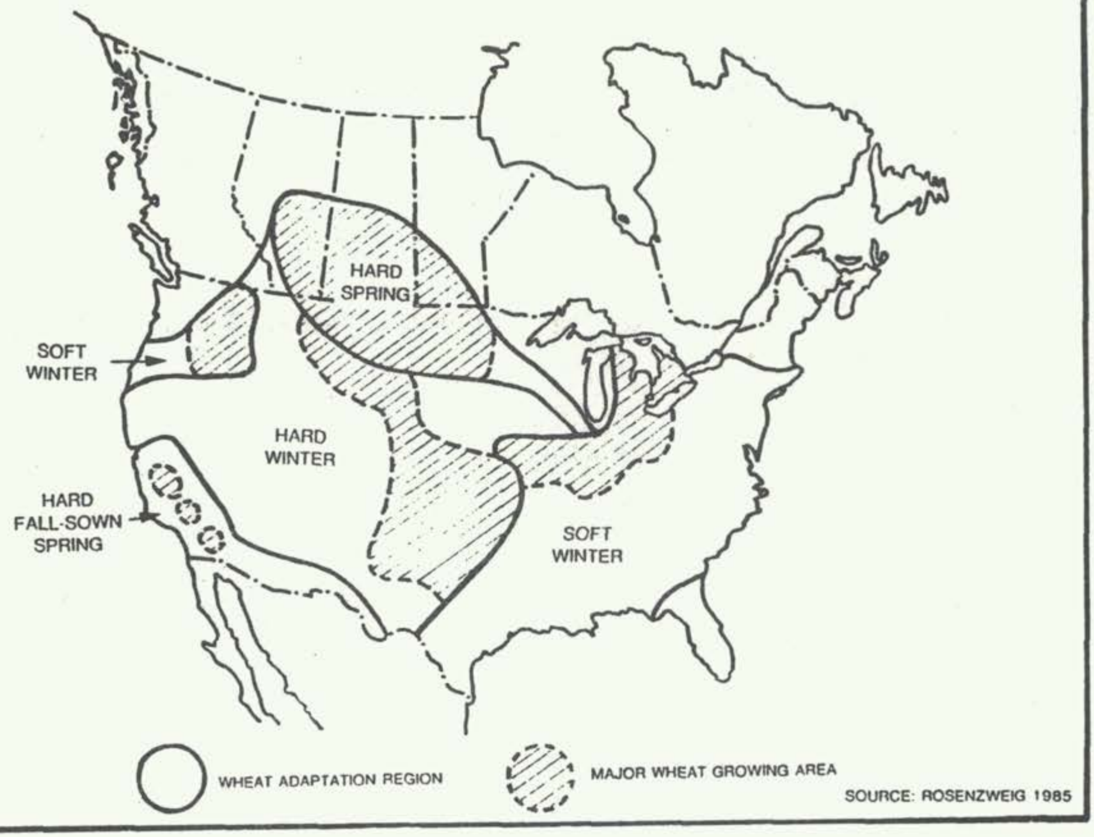
In the Saskatchewan study the effects on spring wheat production were estimated assuming that no changes would occur in the existing production system. No attempt was made to look at changes in crop zonation, that is the movement in major crop boundaries or replacement of crops by others as a result of the environmental changes incurred.

Rosenzweig (1985) attempted to assess the implications of the GISS results for a doubling of CO_2 concentration on North America wheat zonation (Figure 5). Applying the environmental criteria listed in Table 3 to the GISS climate projection, Rosenzweig derived the wheat zonation map illustrated in Figure 6 in the form of an 8° latitudinal x 10° longitudinal grid framework covering the land mass area of North America. Results clearly indicate that the northern boundary of the winter wheat belt in the United States, which currently parallels the mean minimum January temperature of -13°C, would shift north and east into Canada.

In the case of winter wheat expansion into the Canadian Prairies, the major constraint today is overwinter survival, determined to a large extent by minimum winter temperature extremes and snow cover. Technological improvements in varieties and production techniques over the last decade appear to be overcoming the winter survival problem and winter wheat production is expanding. For example, since 1976 winter wheat hectarage in Saskatchewan has increased from virtually zero to over 375,000 ha in 1986 (Saskatchewan Agriculture, 1987). Although technology improvement is

FIG. 5

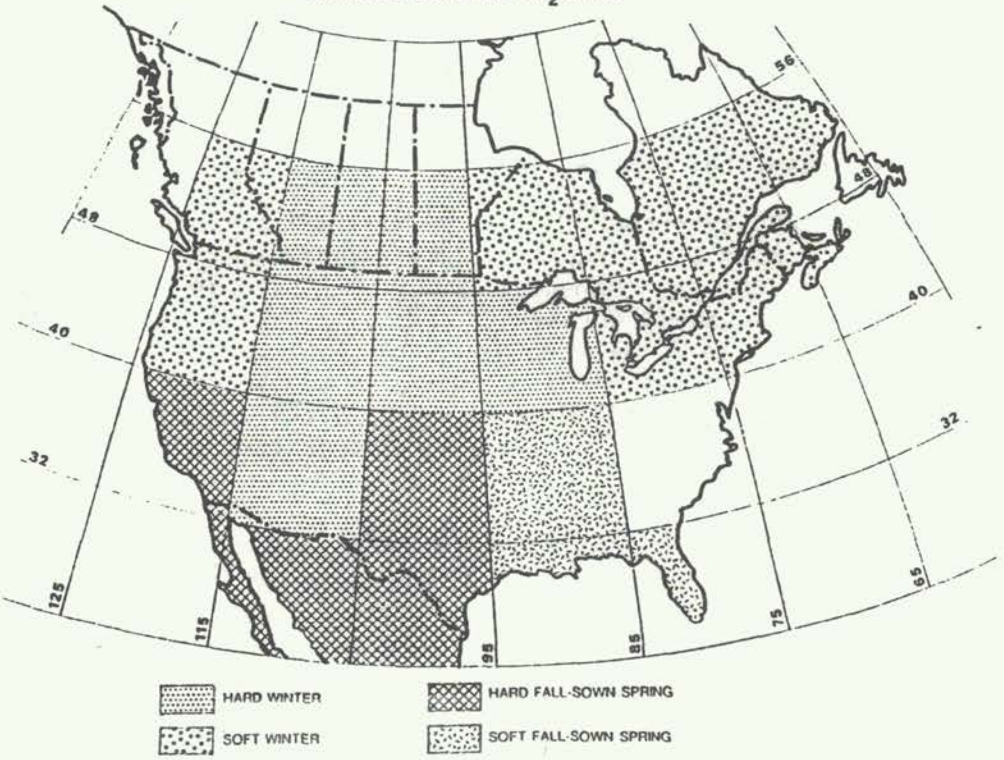
MAJOR WHEAT-GROWING AREAS OF NORTH AMERICA



SOURCE: ROSENZWEIG 1985

FIG. 6

SIMULATED NORTH AMERICAN WHEAT REGIONS USING THE GISS-GCM DOUBLED CO_2 DATA



SOURCE: ROSENZWEIG 1985

undoubted the major reason for winter wheat expansion, climatic warming currently underway has also contributed. Hansen et al. (1981), for example, have found evidence that global temperatures have risen about 0.2°C since the middle of the 1960's. Similar results have been recorded by Shewchuk (1984) for climatic analysis of the last two decades in Saskatoon, Saskatchewan. Should this warming trend continue winter wheat hectarage and production will continue to increase, assuming new markets can be found and exploited. As to whether winter wheat will replace spring wheat production on the Canadian prairies only time will tell. Certainly, if summer droughts become more frequent and severe, logic would suggest that this would be the case. However, future market conditions, improvements in technology, and the possible development of more heat and drought resistant varieties will ultimately determine this.

Table 3: Environmental Requirements for Wheat Used in Classification of Wheat-Growing Regions of North America

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

from Rosenzweig (1985)

CONCLUSION

Results from work undertaken in Saskatchewan suggest that the possible changes in the long term climate of the Canadian Prairies resulting from the GISS general circulation modeling experiments for a doubling of atmospheric

CO_2 would have a major impact on the agroclimate. The growing season length in the Prairies would increase by an average 48 days and precipitation from 11 to 14%. The impact of these changes would be a reduction in long term spring wheat yield and production potential by 6 to 28%. Given the magnitude of the temperature increases projected any decrease in precipitation from current levels could reduce production significantly.

Further, analysis suggests that the Prairies would become more drought prone with droughts occurring with greater frequency and severity. The effect of this is likely to be an increase in annual yield variability and production. A probable consequence of this situation will be a shift of the winter wheat belt from the U.S. into Canada. A shift to fall sown crops in the existing agricultural area would enable farmers to take advantage of increased fall and early spring moisture levels, enabling crops to develop and mature before the onset of drought conditions in June and July.

ACKNOWLEDGEMENT

The author would also like to express his appreciation to a number of individuals for their contribution in preparing this paper. Thanks are extended to W.J. Blackburn for reviewing this manuscript, to D. Murray for help in preparing the figures, and to R. Muma for preparing the computer programs and generating the required data.

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ECONOMIC EFFECTS OF CLIMATE CHANGE ON AGRICULTURE IN THE CANADIAN PRAIRIES

by

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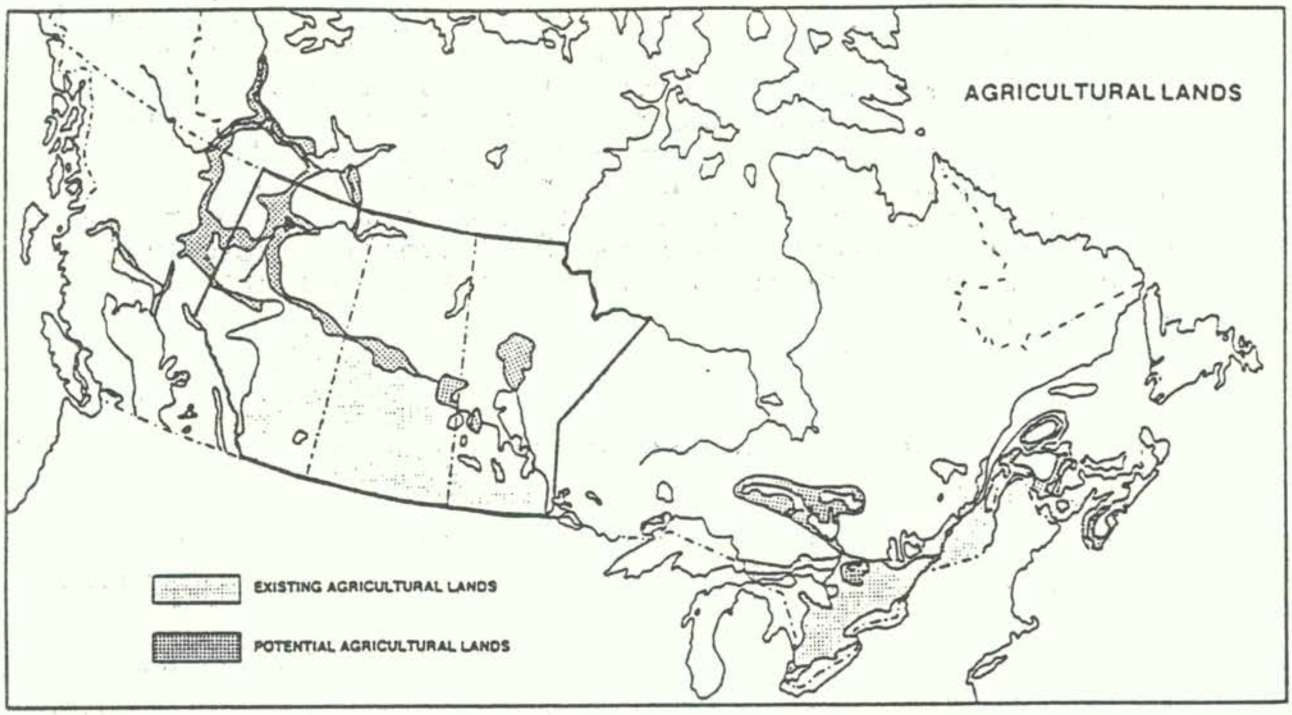
The "Greenhouse Effect" generally refers to a gradual climatic warming associated with increased concentrations of carbon dioxide and trace gases. Predictions of the eventual effects of this warming trend range from more frequent droughts to a booming arctic economy, northern prairie orchards, and a U.S. midwestern desert. Of course, most of the latter predictions are based on pure (sometimes hopeful) speculation. Nevertheless, scientists believe that the climatic changes will be great enough that we need to develop a strategy for coping with the issue now. Possible directions for addressing the issue include adapting to the changing climate, technological control of emissions, reducing activities that emit greenhouse gases, and counteracting the effects of trace gases in the atmosphere. The latter approach is possibly the least promising as it implies global weather modification procedures, although reducing emissions will also be difficult.

The study described below addresses the alternative of adaptation by estimating magnitude of impacts of climate change on the Canadian prairie agricultural sectors (region outlined in Figure 1).

ESTIMATING THE GREENHOUSE EFFECT SCENARIOS FOR IMPACT ANALYSIS

The climatic models linking increased carbon dioxide concentrations to climatic effects are generally

Figure 1



A warmer climate would expand the northern limits of agriculture into areas where soils are suitable.

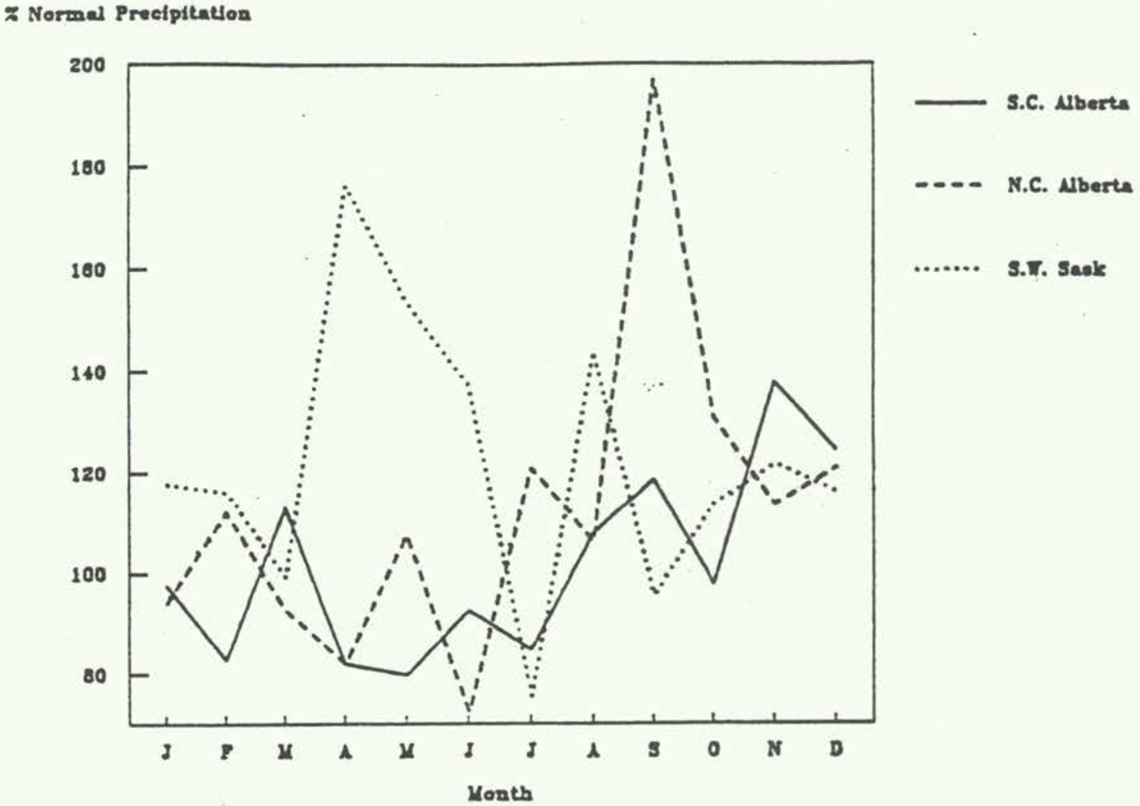
Source: Environment Canada

three-dimensional models of atmospheric circulation, so-called general circulation models (GCMs). The GCMs are selected both for their ability to explain current climate and for their relatively fine temporal and spatial resolutions. Despite the resolution advantages of GCMs, the resulting data usually are not provided at a resolution sufficient to support many agricultural impact models. Temperature and precipitation predictions were provided for this study as monthly averages. This monthly resolution is extremely fine from a climatological point of view, but crop yield models used in determining economic impacts on agriculture often require daily temperature and moisture conditions, including the specification of minimum and maximum temperatures within a day. Clearly, increased <u>minimum</u> temperatures early in a month critical to spring seeding will produce quite different crop yields from increased <u>maximum</u> temperatures later in the same month.

The geographic resolution of GCM results is suitable for aggregate (e.g., national) impact analyses, but is not adequate for analysis at a regional level. The GFDL and

GISS model results used in this study, for instance, provided temperature and precipitation data for grid points ranging from 4.4 to 8 degrees latitude and from 7.5 to 10 degrees longitude. (This distance is approximately 300 to 500 miles north to south and 400 to 500 miles east to west.) Temperature and precipitation estimates can vary dramatically across neighboring grid points (e.g., see Figure 2), and thus, various arbitrary distributions between grid points produce very different results. Greater density of weather recording stations--particularly for recording precipitation events, which can be extremely localized--is likely necessary before geographic resolution can be improved.

Figure 2. Precipitation Changes, Scenario A



The errors of GCMs for 1 x CO_2 (that is for simulations of current concentrations) have been estimated at a factor of 2 for precipitation and up to 5 degrees Centigrade for temperature. Thus, small temperature changes under a hypothetical CO_2 scenario (e.g., 2 x CO_2) become difficult to evaluate. Sensitivity analysis, such as use of temperature changes from various GCMs, becomes necessary. In the case study discussed below, several variations in temperature and precipitation were used.

A further problem with GCM-generated climatic scenarios is that they give changes in long-term normal conditions, but provide no indication of the distribution of the changes across years. Thus, questions remain concerning any expected changes in the variability of weather. Weather variability is as important a constraint to prairie agriculture as long-term average climate.

Despite these and other difficulties in determining the economic impacts of climate change using currently available climatic scenarios, such impact studies can provide general indicators of the magnitude and direction of expected effects.

CASE STUDY: EFFECTS OF CLIMATE CHANGE ON PRAIRIE AGRICULTURE

The Climate Change Scenarios

Two climatic change scenarios, called A and B, were provided by the Canadian Atmospheric Environment Service (AES) based on GCM experiments undertaken using the GFDL and GISS models. AES compared these results to results from similar experiments for 1 x CO_2, i.e., simulated normal baseline conditions, to derive monthly changes in temperature and precipitation (Table 1). These monthly average changes were then added to historic, daily weather data for each year from 1961 to 1985 using a flat distribution (referred to as Scenario A and B) or a trigonometric distribution (Scenarios A2 and B2). (Daily data can be generated by GCMs but are extremely expensive to save.) Economic and agronomic effects of these climate change scenarios are compared to simulated effects of long-term average weather (1961-1985 average weather used as the "baseline") and of a major historic drought; 1961 weather was used for the latter scenario, as it caused the most severe and widespread prairie agricultural drought in recent record.

Table 1

Climatic Change Scenarios: Descriptive Statistics

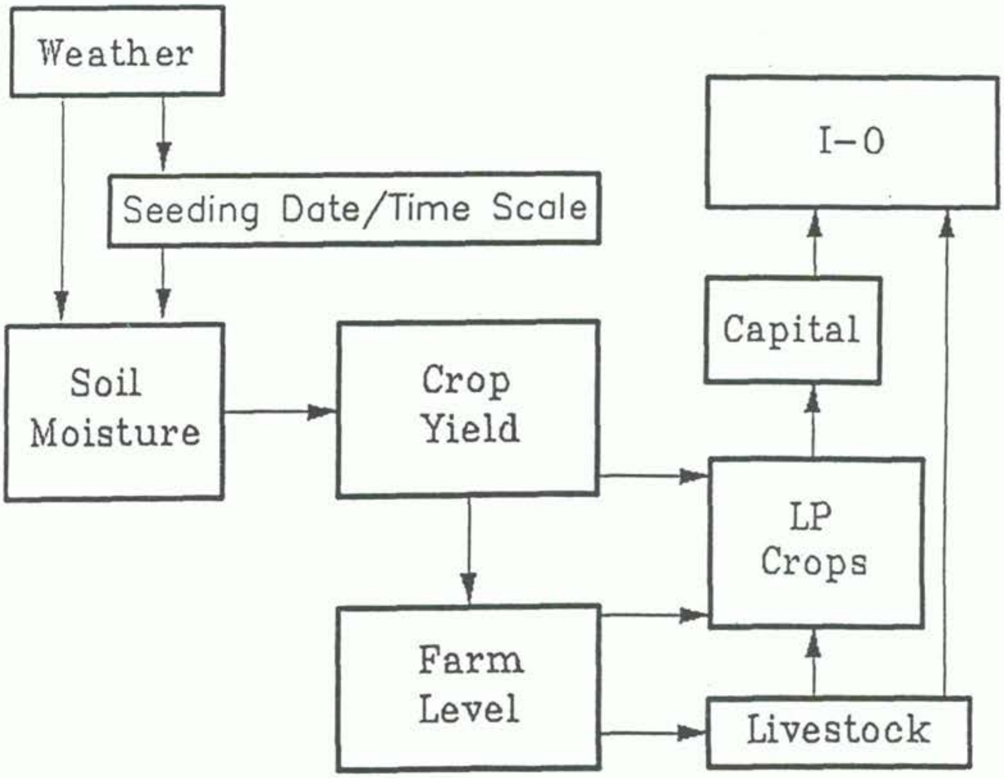
	Scenario			
	A		B	
	So. Man.	No. Alb.[a]	So. Man.	No. Alb.[b]
Temperature Change (+C)[c]				
Average (annual)	2.57	2.79	4.58	4.64
Standard Dev.	1.44	1.46	.96	1.06
Low (month)	0.40 (July)	1.20 (Feb., Nov.)	3.10 (July)	3.30 (June, July)
High (month)	6.00 (April)	6.10 (April)	5.70 (Jan., Dec.)	6.20 (Jan., Dec.)
Precipitation Charge (% normal)[c]				
Average (annual)	128.07	114.85	113.87	122.14
Standard Dev.	28.62	28.75	8.09	11.58
Low (month)	88.80 (Mar.)	72.40 (June)	95.80 (Sept.)	100.00 (Sept.)
High (month)	171.50 (Apr.)	196.80 (Sept.)	123.50 (Jan., Dec.)	141.20 (Jan.)

[a] Approximately Peace River region.

[b] Approximately Edmonton region.

[c] Change from 1 x CO_2 experiments.

Figure 3: Model Flows



Methods

A series of models was developed to simulate economic responses to weather. The models are primarily deterministic and the linkages among models unidirectional (Figure 3). The model series begins with weather models, which translate the monthly long-term averages of the climate change scenarios into daily temperatures and moistures at the numerous prairie weather stations.

Due to the need to simulate artificial weather scenarios, an algorithm was developed to simulate the seeding decision (seeding date) and thus the time scales used to calculate a crop's daily progress toward maturity for both historic and simulated (scenario) weather. Seeding and maturity dates under increased carbon dioxide are generally earlier than the historic dates. The new seeding and stage dates are used with the new weather to estimate soil moisture stresses for the various crops in all prairie locations. The soil moisture model (from Agriculture Canada) is a biological/physical simulator that estimates soil moisture as a function of potential evapotranspiration, crop rooting pattern, precipitation, runoff, snow melt, and soil moisture release characteristics.

Soil moisture stresses are only one of many factors which influence crop yields. The crop yield models quantify the relationships between crop yields and moisture stresses, chemical use, seed variety, seedbed (stubble versus fallow), extreme weather events such as frosts and floods, and location via regression equations. Yield equation have been estimated for 40 crop subdistricts and five major crops (wheat, oats, barley, canola (edible rapeseed), flax) in all three provinces. (In Manitoba, yields are also modelled for winter wheat, rye, grain and silage corn, sunflowers, tame hay, and native pasture, as well as some grains under reduced tillage techniques.)

The predicted yields for each scenario are then used to determine economic impacts of climate change in each province. In the case of Manitoba the yields are entered into a linear programming (LP) model which uses the predicted yields to adjust cropping patterns to maximize net crop revenues, given physical, biological, and economic constraints on the sector. The Manitoba crop revenues, expenditures and farm household incomes simulated by the LP model are then used as inputs to an Input-Output (I-O) model of the nonagricultural sectors of the Manitoba economy, thereby determining scenario effects on agriculturally linked sectors of the economy.

For Alberta and Saskatchewan economic impacts on the agricultural sectors were extrapolated directly from summations of the yield effects multiplied by current (1985-1986) crop prices. I-O models for these provinces were used to determine impacts on nonagricultural sectors.

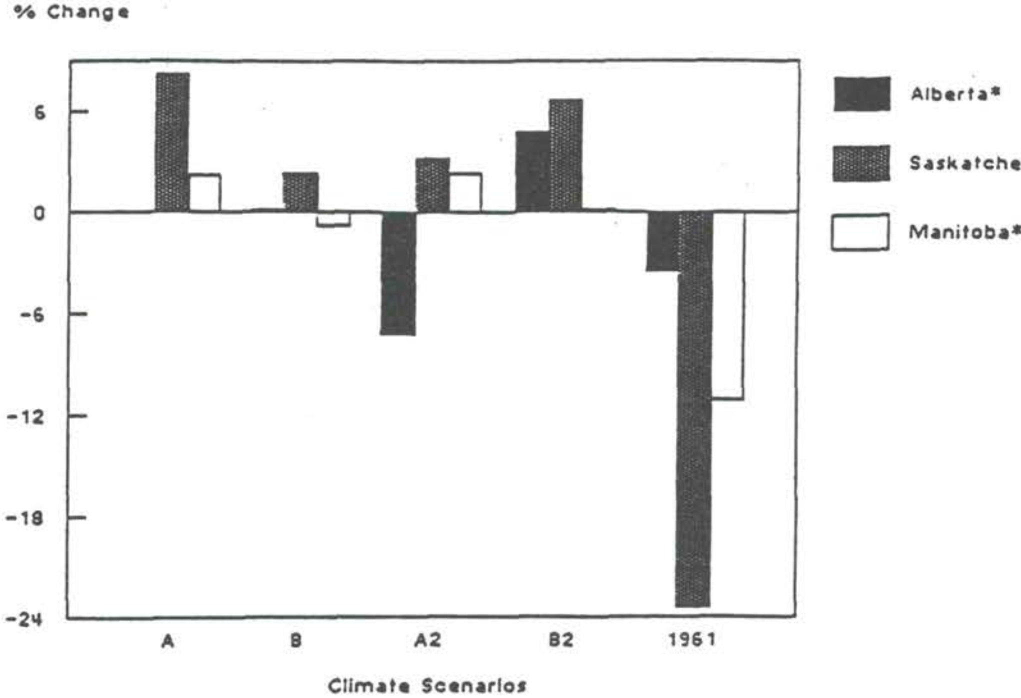
Results and Conclusions

The patterns of results vary so dramatically across crops, regions, baseline years and scenarios that generalizations become difficult. Therefore, only aggregate economic results are discussed here.

Agriculture. While temperatures rise under all climatic change scenarios, in some prairie regions the increases are small during the growing season (e.g., .8 degrees Centigrade in June and .4 degrees Centigrade in July for Scenario A in central and northern Saskatchewan). In such areas slight increases in precipitation can offset increases in evapotranspiration, or earlier seeding (e.g., due to 6.4 degrees Centigrade increase in April in the same scenario and region) can result in a new crop growth time scale (relative to historic patterns) and enhanced production volumes. The increases in production in these regions are often offset by decreases in other regions (or vice versa), resulting in reduced province-wide effects. Therefore, most of the estimated economic impacts of climate change are small; provincial crop revenue gains or losses generally range from one to eight percent (Figure 4). The greatest impacts of climate change include a seven percent revenue decrease under scenario A2 in Alberta, five to seven percent increases under B2 in Alberta and Saskatchewan, and an eight percent increase under A conditions in Saskatchewan. (The Saskatchewan and Alberta results do not allow for adjustments in cropping patterns, partially explaining the larger magnitude of effects in these provinces.)

The impacts of long-term climatic warming do not approach the magnitude of impacts from a 1961 type drought. The 1961 drought caused an 11 percent crop revenue loss in Manitoba, a 24 percent loss in Saskatchewan, and a four percent loss in Alberta. (The 1961 drought was not as severe in all regions of Alberta.) Therefore, increased frequencies of major droughts under climate change represents a greater threat than the long-term increase in temperatures per se. Unfortunately, the changes in frequencies of such drought events under the Greenhouse Effect are not known.

Figure 4. Percentage Change in Crop Receipts by Scenario



*Wheat, barley and canola
**All crops

Other Sectors. Economic effects on other sectors of the provincial economies (as modelled in I-O models) are related to changes in the farm sectors' expenditures for farm inputs and consumer goods and services; while on-farm expenditures remain fairly constant across climatic scenarios; discretionary expenditures of households and enterprises (e.g., farm equipment) change in response to changing cash flows. For example, if net revenues in the Manitoba agricultural sector decline in the long run, production activities in sectors servicing agriculture will decline as well. (In aggregate, the decline will be nearly proportional.) For instance, under continuing droughts output and employment could be expected to decline in all sectors but feed manufacturing (as more supplements will be purchased). The greatest losses would be felt in the trade and service sectors which are affected by declines in farmers' discretionary expenditures.

ASSESSING THE IMPLICATIONS OF CHANGES IN CARBON DIOXIDE CONCENTRATIONS AND CLIMATE FOR AGRICULTURE IN THE UNITED STATES

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Abstract

This paper describes and demonstrates a methodology for the assessment of effects upon agriculture stemming from the accumulation of radiatively active trace gases in the atmosphere. Changes affecting agricultural productivity include the increase in atmospheric concentration of carbon dioxide and climate changes. The consequences of each of these effects are analyzed separately and and in combination to illustrate the importance of a comprehensive evaluation. The analysis also demonstrates the role of adjustments induced by a market economy in reallocating resources in response to environmental changes. Particular emphasis is placed upon assessing changes in both dryland and irrigated crop acreages as well irrigation water use. The implications for further research and policy are drawn in conclusion.

Environmental Change Effects on Agricultural Productivity

As one of the most weather sensitive sectors of our economy, agriculture is expected to be profoundly affected by climate changes. However, climate change is only one dimension of the range of impacts that agriculture is expected to face from the collection of environmental changes known as the greenhouse effect. The accumulation of several trace gases in the lower atmosphere that are radiatively active absorbing infrared radiation is the cause of this effect. Some of these gases, for example chlorofluorocarbons are implicated in stratospheric ozone depletion which has other severe environmental consequences. Increased ultraviolet radiation from a reduced ozone layer would directly reduce crop productivity (Teramura, 1986). Increased smog would also be produced with detrimental effects on crops (Heck, et. al., 1983).

Other trace gases, for example carbon dioxide, have beneficial direct effects upon plant productivity (Strain and Cure, 1985). The atmospheric concentration of CO_2 effectively limits photosynthetic processes and therefore ultimate crop productivity. Increasing the concentration raises this limit and increases productivity, an inadvertent fertilization. Many of the activities producing these CO_2 increases also produce other atmospheric emissions such as ambient ozone precursors which have deleterious effects on plants. For a more complete discussion of the range of interrelationships and impacts between economic activity, environmental changes, and agricultural productivity see Dudek (1987b).

It is well known that the fortunes of the agricultural sector are highly weather dependent. While accommodating to temperature, precipitation, and storm variability are a common occupation in agriculture, the contemporary industry has not had to contend with actual climatic change. Such changes are anticipated to include increased temperatures, different precipitation patterns, altered evapotranspiration, and changed frequency and intensity of storm events. Large scale computer models of the earth's atmosphere and climate, termed general circulation models (GCM's), are the primary means by which such changes are predicted. While a variety of GCM's exist, one scenario from only one such model, the Goddard Institute of Space Studies' (GISS) GCM, is employed in this analysis. GCM's require the specification of expected trace gas emissions over time producing a scenario which describes climate changes as a result. A frequently analyzed scenario, also assessed in this paper, is the path to an atmosphere in which the concentration of CO_2 has doubled.

The GISS GCM has a spatial resolution of either 8 degrees latitude by 10 degrees longitude or 4 degrees by 5 degrees depending upon analytical needs (Hansen, *et. al.*, 1983). Results on an 8 x 10 basis have been used in the research reported in this paper. The model simulates climate by solving the fundamental equations for conservation of mass, momentum, energy, and water. The GISS GCM has an equilibrium global mean sensitivity of 4.2 degrees Celsius for doubled CO_2 (Hansen, *et. al.,*, 1984). The doubling scenario results employed in this analysis assume continued growth in trace gas emissions. Consequently, no account is taken of the effect of the recent Montreal protocol upon chlorofluorocarbon emissions. The GISS GCM simulation experiments and results are described in Hansen, *et. al.* (1986).

The degree of correspondence between the 8 x 10 grid boxes for which GCM results are produced and state boundaries varies with the size of state. For example, grid box 1707 covers most of California and Nevada. In this research, GCM model resolution and the spatial scale for agricultural modeling were roughly matched. Table 1 presents GISS GCM results for temperature and evapotranspiration changes under a doubled CO_2 atmosphere. These climatic changes are reported for the agricultural production regions employed in this study (see Figure 1). The Northeast region at 3.7 degrees C increase shows the smallest change, while the Corn Belt and Delta States regions are predicted to experience the greatest rise at 5.3 degrees C. Evapotranspiration changes are much more ranging from 22% increases in Washington and Montana to only 1% in California and Nevada. However, the significance of these changes for agriculture can only be determined after analysis of their biologic and economic significance.

Assessment Methodology

A variety of approaches to the problem of evaluating the impact of climate change upon agriculture have been pursued. Basically, these studies follow two distinct lines. One approach is typified by the evaluation of historic events in the search for analogs as an aid in understanding response to change. The other line employs detailed computer studies of agricultural systems. The research reported in this study follows the latter approach as the more common method employed to assess the consequences of environmental changes. Computer studies of production response proliferated as economists attempted to analyze environmental problems like salinity, ozone, and acid deposition.

The general approach is to translate environmental changes into biologic responses which can be converted into productivity effects (Wetzstein, 1985). Crop responses, i.e. changed yields, are only one element of the ultimate effect upon farm firm revenues. Productivity changes affect supply response, i.e. the willingness of farmers to produce crops at different prices. Since many agricultural commodities, e.g. wheat, are produced in many locations across the nation in competition for the same customers, these individual effects must be aggregated. Prices for these commodities are determined by the interaction of both supply and demand. Consequently, the effects of market forces in reallocating resources and crops in response to productivity changes must be assessed.

Biologic response models have dramatically improved in recent years, progressing from statistical analysis of experimental data to highly detailed crop growth simulation models (Ritchie, 1984). However ideal, the latter tools are expensive to generate and operate. As a result, only a few crops have been modeled in this detail. Further, since the research reported in this paper is designed to produce an estimate of the relative impact of climate change, crop growth simulators are more precise than warranted. Consequently, general response assessments culled from existing literature have been employed.

Bolin, et. al. (1986) indicate a 10-50% increase in yields for C3 type crops in response to doubled CO_2. C3 type crops, barley, cotton, oats, rice, soybeans, and wheat in this study, are more efficient photosynthesizers than plants in the C4 category. C4 crops, such as sorghum and corn, would only have increases from 0-10%. Midpoints of the C3 and C4 ranges of 30% and 5% respectively were assumed for the direct CO_2 enhancement analyzed in this study. Estimates of climate change effects upon yields, particularly temperature, were drawn from the same source. The review by Bolin, et. al. concluded that yield reductions in the 3-17% range would result from a 2 degree C warming. A midpoint 5% yield decrement per degree C temperature rise was assumed for all crops for this study.

While the CO_2 and temperature effects identified above can be expected to potentially affect land resources devoted to agriculture, other resource use effects are important as well. Changes in the rates of evapotranspiration, identified regionally in Table 1, would affect both regional hydrology as well as irrigation demand (Rind and Lebedeff, 1984). The evapotranspirational changes from Table 1 were combined with Soil Conservation Service (1976) estimates of crop and location specific evapotranspiration rates to produce estimates of irrigation water requirements under the simulated climate change.

While precipitation predictions are available from the GISS GCM as well, several considerations militate against their use. First, the precipitation changes are the most uncertain of the parameters simulated. Second, the difficulty of translating precipitation changes into effective water supplies, both in surface impoundments and in groundwater aquifers, is beyond the scope of this effort. Lastly, the "snapshot" nature of this assessment does not consider changes in resource availabilities over time. On-going assessments are evaluating the implications of water supply changes (Dudek, 1987a). The current study evaluates changes in irrigation

TABLE 1. Temperature and Evapotranspirational Changes by Region

PRODUCTION REGION	TEMPERATURE CHANGE (degrees Celsius)	EVAPOTRANSPIRATIONAL CHANGE (percent)
Appalachia	3.9	9
Arizona	4.9	5
California	4.4	1
Corn Belt	5.3	7
Colorado	4.9	5
Delta States	5.3	7
Idaho	4.8	20
Kansas	4.6	9
Lake States	4.7	12
Montana	4.8	22
Nebraska	4.9	3
North Dakota	4.5	14
New Mexico	4.9	5
Northeast	3.7	2
Nevada	4.4	1
Oregon	5.0	15
Oklahoma	4.6	9
South Dakota	4.9	3
Southeast	3.9	9
Texas	4.3	11
Utah	4.9	5
Washington	3.9	22
Wyoming	4.8	20

Sources: GISS GCM temperature changes for doubled CO_2 were supplied by the U.S. Environmental Protection Agency's Office of Policy, Planning, and Evaluation to participants in the Symposium on Climate Change in the Southern United States. Evapotranspirational changes from the GISS GCM were taken from Rind and Lebedeff (1984).

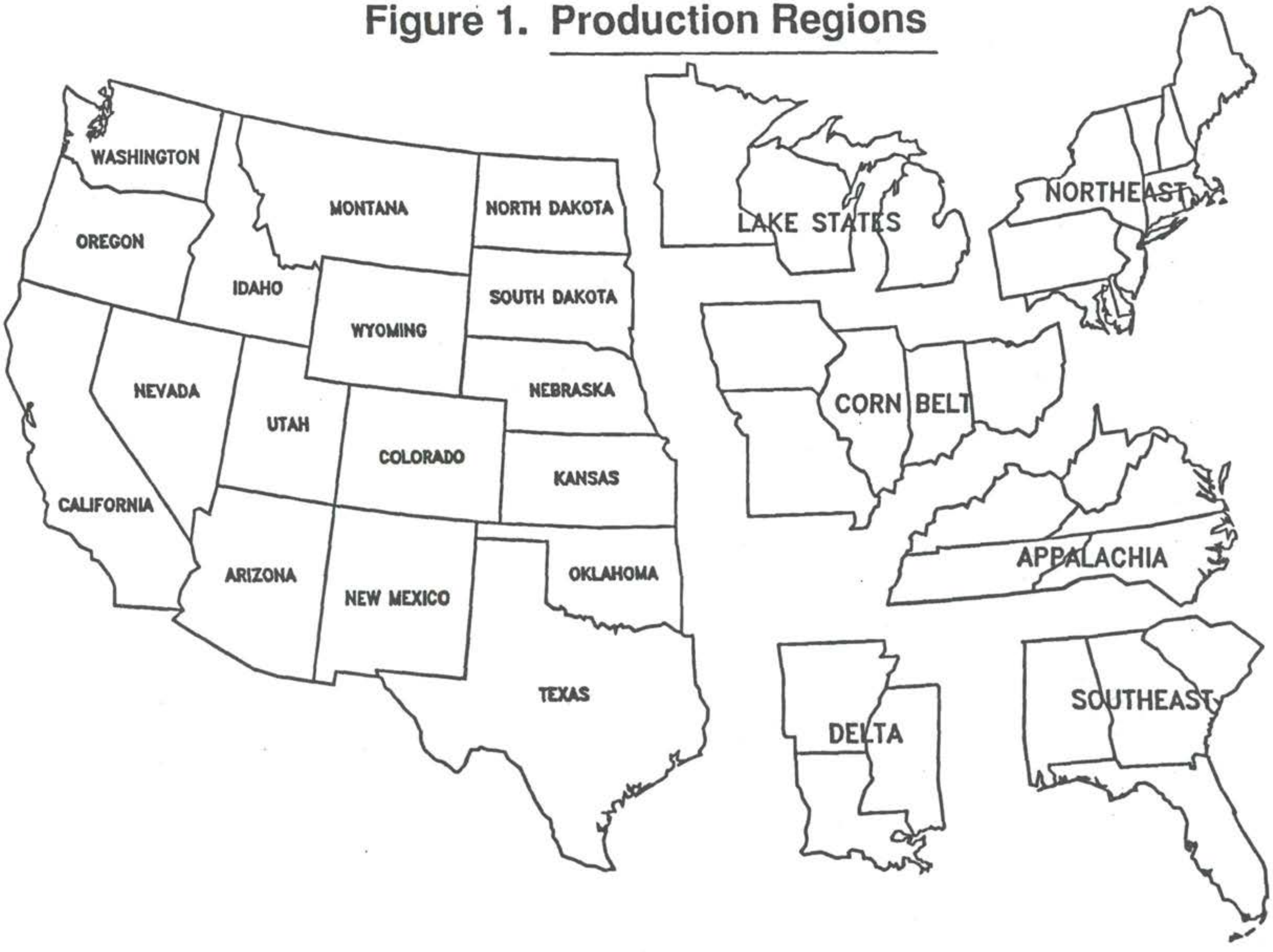
demand only against existing, developed water supplies.

This research differs from previous analyses (see for example Rosenzweig (1985)) of the effects of climate change upon agriculture in the use of a national agricultural model. The Western Resources Model (WRM), emphasizing greater spatial detail for the 17 western irrigated states, is derived from the model reported by Horner, et. al. (1985). The individual agricultural production regions represented within the WRM are displayed in Figure 1. Each of the 17 western states is separately modeled, while eastern U.S. agriculture is represented by 6 aggregated production regions. This difference in spatial detail within the model reflects the study's hypothesis that irrigated regions, despite their high degree of management control over water inputs, are likely to be more sensitive to climatic changes.

Crops included in the study include the principal grain and commodity program crops produced in the United States; barley, corn, cotton, oats, rice, sorghum, soybeans, and wheat. The WRM uses baseline information concerning resource availability, crop acreages, production costs, and resource use derived from published 1982 agricultural statistics. The structure of the model and data sources are more completely described in Dudek (1987c). However, fundamental changes in the dimensions and activities of the two models render the analysis reported in that paper uncomparable with the results from this model. The crop yield and resource requirement changes derived from the biologic and agronomic responses described above are translated into regional terms for analysis by the WRM.

Technically, the WRM is one of a class of quadratic programming models designed for agricultural analysis. Its main virtues are the simulation of market outcomes and spatial detail describing resource use. The WRM is a normative model which describes outcomes that "should" result from the scenario changes introduced into the model. However, the resulting outcomes should not be construed as forecasts, since no attempt has been made to forecast the myriad parameters required to portray the state of U.S. agriculture 40-70 years hence. Rather, the analysis presented is more aptly likened to a polaroid capturing a snapshot of the state of agriculture at one time under a specific set of circumstances. Dynamic economic models which would track the evolution of the agricultural system over time are currently very limited.

Figure 1. Production Regions



The WRM allocates resources and crop production among the regions given estimated climatic effects and resource supplies so as to maximize measures of producer and consumer welfare. The model allows supply response both in terms of changes in resource use as well as changes in the costs of production. For example, if groundwater is pumped in greater quantities, then the cost of pumping per acre-foot increases to reflect the greater depths from which the water would have to be withdrawn and greater energy use as well as the increased investment in wells and pumps. Land resource costs also vary in response to the intensity of cropland use. The inclusion of land conversion cost functions allows a more realistic appraisal of the effects of land use changes in response to environmental changes and economic forces.

It is important to emphasize the assumptions underlying the WRM. Current crop production technology is employed. As Decker, et. al. (1986) have noted, plant breeding has contributed significantly to the current high level of agricultural productivity and is likely to play a role in mitigating any adverse effects of climate change. No predictions concerning the efficacy of such future developments are included in this model. Further, as climatic change occurs around the global, international trade in agricultural commodities is likely to be altered. As Horner, et. al. have demonstrated, changes in export demand exert a powerful influence on agriculture and resource use. Current trade relationships only are assumed. Lastly, only the current stock of resource supplies are available for agricultural production. No further large scale development of water resources is anticipated.

Comparing Carbon Dioxide Concentration and Climate Change Impacts

The two major components of the changes associated with the greenhouse effect important for agriculture are changes in the ambient concentration of carbon dioxide and changes in climate. It has long been recognized that these changes are potentially significant for agriculture (National Defense University, 1980). Research concerning these agricultural implications has often focused on one set of effects or the other. Clearly, what is need is an assessment of the net effect of these changes on agricultural productivity. To illustrate the importance of assessing the net effect, this paper contrasts the results from focusing on a single set of effects in isolation with a combined analysis of all effects. An interesting by-product of this approach is a comparison of the relative magnitude of each of these effects when modeled separately.

The most immediate question concerning the impact of these changes concerns the total quantities of food and fiber produced, i.e. will supplies be adequate in current terms of reference? Figure 2 presents the equilibrium quantities of commodities produced and marketed under each of the scenarios analyzed. As anticipated from the assumptions defining crop response, crop production is increased under the CO_2 only scenario. The direct effect of CO_2 enhancement acts as free fertilization boosting output. However, production does not increase linearly by the 30% and 5% factors applied for C3 and C4 crops due to the moderating influence of market forces, i.e. the diminishing desirability of increasing quantities of food. The C4 crops, sorghum and corn, exhibit the least change.

The climate change scenario, analyzing only temperature and evapotranspirational changes, shows strong declines in production. Since the modeled effects are uniformly negative, this result is hardly surprising. Rice production, requiring between 2 to 6 acre-feet of water per acre, is reduced so sharply as a result of intense competition for available water supplies. Offsetting the productivity declines are increases in crop prices in response to reduced production and increases in the resources devoted to agriculture. Of particular note is the relatively greater magnitude of production effects under the climate change scenario when compared to the doubled CO_2 only result. Combining the two sets of effects produces more moderate absolute changes. Only corn and sorghum have relatively large reductions in production. As C4 crops benefit the least from the CO_2 enhancement, they are the least able to compete for more resources against other crops and their own cost structure.

To both economists and policy-makers, however, the adequacy question also has a price dimension. What will the impact of these be on consumers' food bills and how will farm income be affected? Figure 3 depicts the equilibrium prices predicted for the three alternative environmental scenarios analyzed. As expected, these outcomes display a pattern of changes directly opposite that for quantities. However, the percentage changes are much larger. For doubled CO_2, corn and sorghum prices drop the least since their production increased the least. Differences in crop price changes are due not only to differences in production changes, but also to differences in demand elasticities, i.e. the responsiveness of quantity changes to price changes. For example, under the climate change scenario, both rice and barley exhibit approximately the same percent reductions in production. However, as Figure 3

Figure 2. Aggregate Crop Production Changes

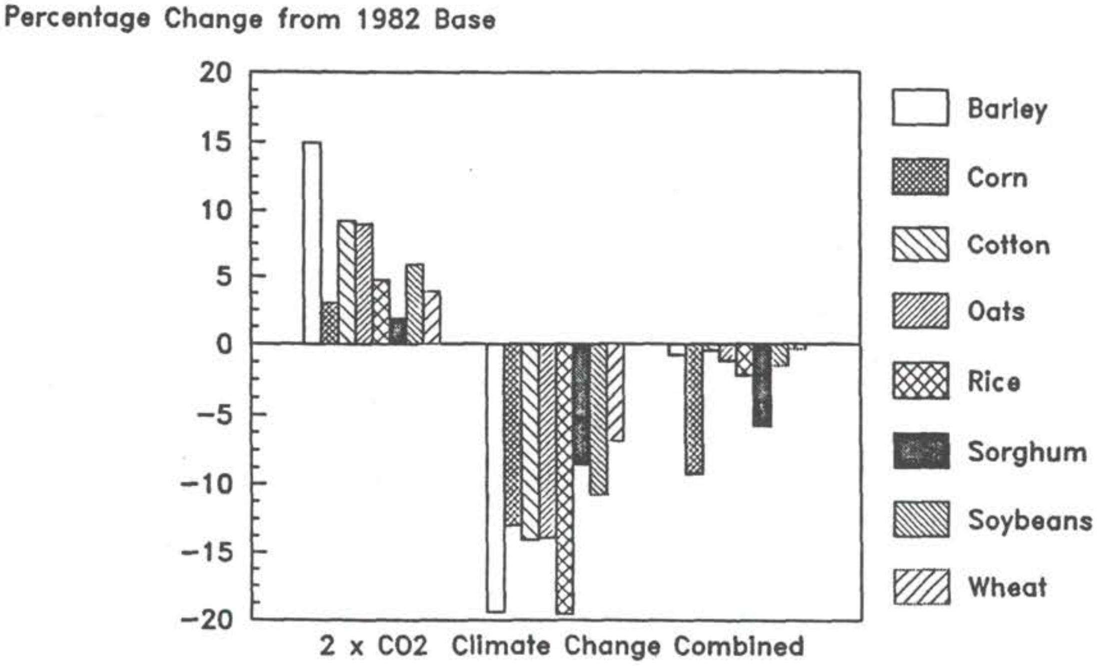
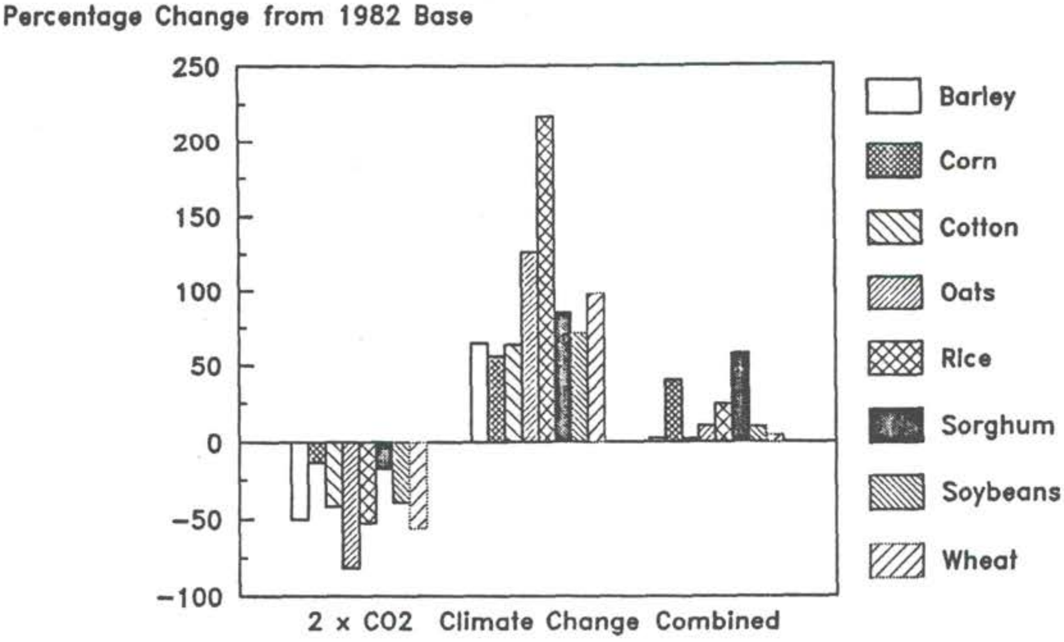


Figure 3. Aggregate Crop Price Changes



demonstrates, the corresponding price changes are markedly different. Barley's demand is more price elastic than that for rice.

As with production, relative price changes are much greater under the climate change scenario than under either of the alternatives. The combined scenario consistently shows the greatest effects on the C4 crops, sorghum and corn. These price changes help to underscore the distributional effects that can be expected under such widespread environmental change. In general, increased prices for agricultural commodities reduce consumer welfare while increasing revenues to agricultural producers. Net changes are complicated by our program of farm subsidies paid to producers from tax revenues levied on consumers. Consequently, increases in farm revenues should help to reduce the level of support payments, all other things being equal, providing a general benefit. However, distributional effects stemming from climate change can only be assessed from a regional perspective not afforded by the aggregate national market outcomes.

Most revealing of climate change impacts across the nation's agricultural economy is the effect upon regional resource use. In many regions of the country, agriculture exerts a powerful influence upon local, regional and state economies. It is also a significant determinant of local environmental quality as agricultural operations are the source of significant environmental insults. Since dryland and irrigated agricultural production are fundamentally different, varying in resource requirements, regional distribution, and response to climatic changes, they are presented separately. Readers may note some differences with previous assessments performed with this model (Dudek, 1987c). The major change is the introduction of nonlinear, i.e. price endogenous forms for all commodities. This version described in this paper runs on a VAX minicomputer while the former model runs on an AT-class personal computer with the usual limits on core memory.

Table 2 presents estimates of dryland crop acreage changes by region for each of the impact scenarios. The base 1982 dryland acreage stood at about 242 million acres for the nation as a whole. The fertilization effect of CO_2 is evident in the roughly 13% reduction in dryland acreage when that effect is assessed in isolation. Climate changes alone bring additional acres into production totaling 18% of base year acreage. Combining the two effects resulted in an overall 5.5% increase in dryland acreage. Regionally, the effects on dryland acreage are most pronounced in the eastern production regions. Figure 4 displays percentage changes in dryland acreages for

TABLE 2. Dryland Crop Acreage Changes by Region by Scenario

PRODUCTION REGION	1982 BASE	CO_2 ONLY	CLIMATE CHANGE	COMBINED
	******** millions of acres ************			
Appalachia	14.572	13.006	17.660	16.064
Arizona	0.016	0.013	0.019	0.017
California	0.801	0.715	0.894	0.815
Corn Belt	76.479	68.249	88.151	80.554
Colorado	3.102	2.450	3.818	3.158
Delta States	15.814	13.790	17.214	16.112
Idaho	1.362	1.106	1.591	1.398
Kansas	17.349	14.238	21.575	18.388
Lake States	26.740	23.783	32.158	28.705
Montana	6.642	5.219	7.987	6.764
Nebraska	9.122	8.133	10.513	9.614
North Dakota	14.146	11.107	17.289	14.625
New Mexico	0.623	0.533	0.745	0.648
Northeast	5.470	5.092	6.341	5.986
Nevada	0.012	0.009	0.013	0.012
Oregon	1.250	1.030	1.493	1.261
Oklahoma	7.970	6.775	9.481	8.144
South Dakota	9.898	8.423	12.183	10.500
Southeast	11.423	10.382	13.195	12.092
Texas	15.335	13.409	18.409	16.440
Utah	0.260	0.199	0.320	0.264
Washington	3.217	2.685	3.876	3.339
Wyoming	0.354	0.294	0.425	0.359
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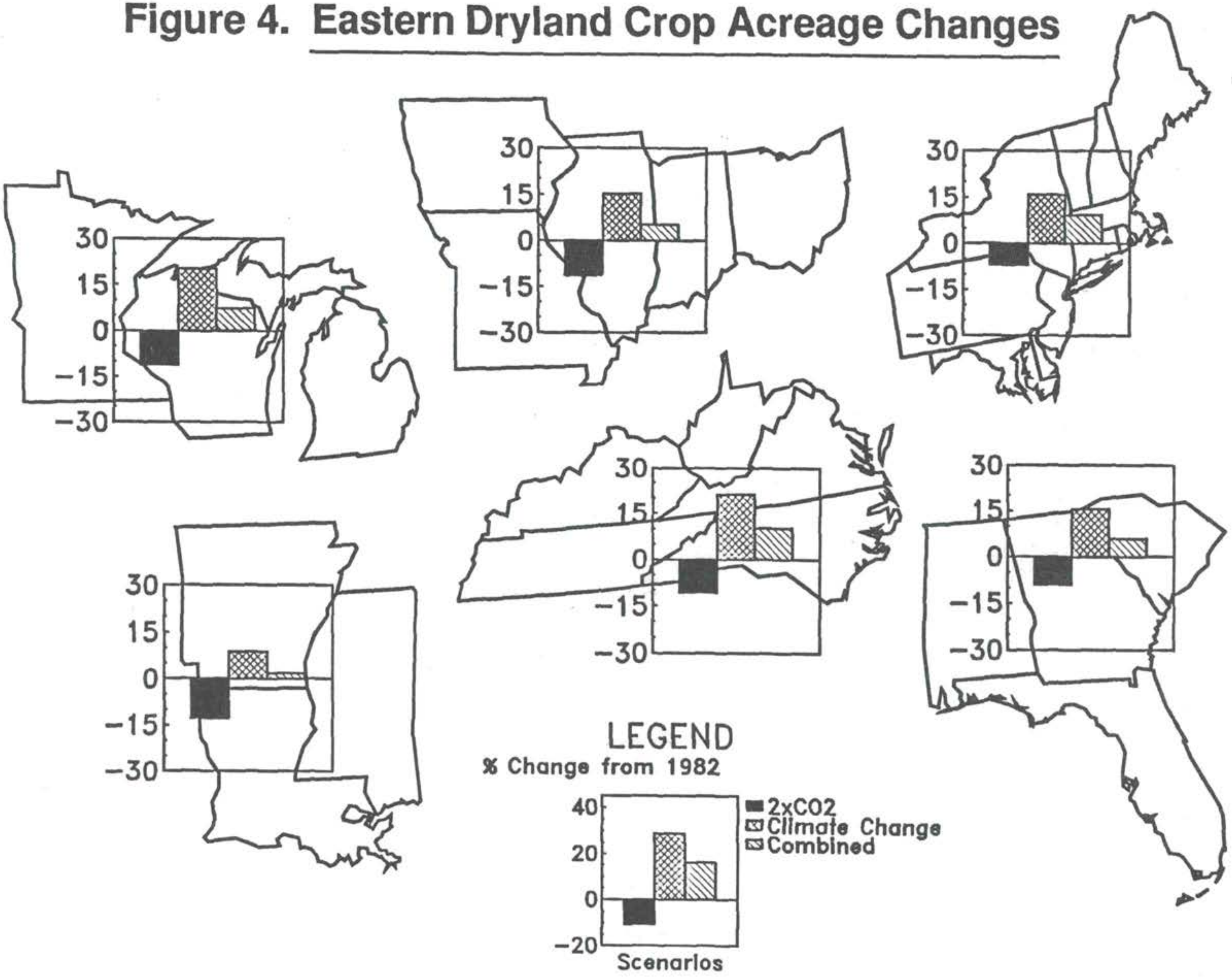
TOTAL	241.957	210.640	285.350	255.259

Figure 4. Eastern Dryland Crop Acreage Changes



each of the production regions and scenarios. Under the doubled CO_2 scenario, dryland acreage changes cluster around -10%. Climate change only effects are generally greater in absolute value, but not so uniform, however. For both the climate change and combined scenarios, the latitudinal gradient of effects predicted by the GISS GCM begins to be evident. All of the more northerly eastern production regions show greater sensitivity to climatic change. Actual acreage changes are greatest in the Corn Belt since its base acreage at 76.5 millions acres dwarfs all other regions. Even the seemingly modest 5% increase projected under the combined scenario translates into a whopping 3.8 million acre change.

Figures 5 and 6 display dryland acreage changes for the arid southwest and the pacific northwest. In each case, acreage changes for the doubled CO_2 only and climate change only scenarios were more nearly equal, although opposite in effect. The northern tier of southwestern states showed the strongest percentage changes of any of the regions in the West. Among the southwestern states, however, the largest absolute changes occurred in Kansas and Texas with approximately 1 million acre increases each under the combined scenario. The importance of comprehensive effects assessment is most in evidence in the dryland results for these western regions. Both of the single effect scenario produced strong directional changes in most of the regions. However, when combined in a single scenario, many of the individual regional percentage changes were below the national average of 5.5%.

Although only about 10% as large as total dryland acreage, irrigated cropland dominates many of the western production regions. For example, in this model, California had 0.8 million dryland acres, but over 3 million irrigated acres. Table 3 presents the base year's irrigated acreage and the irrigated acreage estimates for each of the scenarios. California, the Delta States, Nebraska, and Texas together account for about 60% of the nation's irrigated acreage. In the aggregate, the doubled CO_2 scenario resulted in a 12% decline in acreage from the base year. Climate change effects in isolation produced an overall 8% increase, while the effects combined produced a modest increase of 1.6%. Individual regional changes are portrayed in Figures 7 and 8.

Latitudinal gradients in the estimated effects are clearly in evidence from Figures 7 and 8. The production regions of the northwest show increased sensitivity and response under all of the scenarios analyzed. However, in each case, as throughout the West, the real issue is water. What is the implication of these irrigated acreage changes for water demand

Figure 5. Southwestern Dryland Crop Acreage Changes

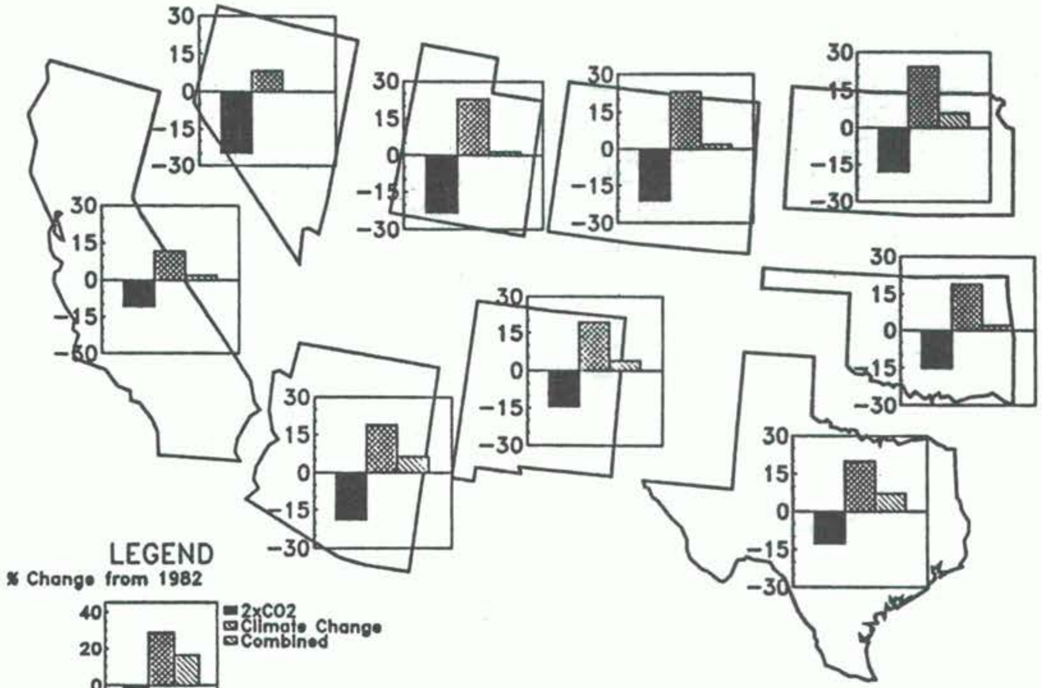


Figure 6. Northwestern Dryland Crop Acreage Changes

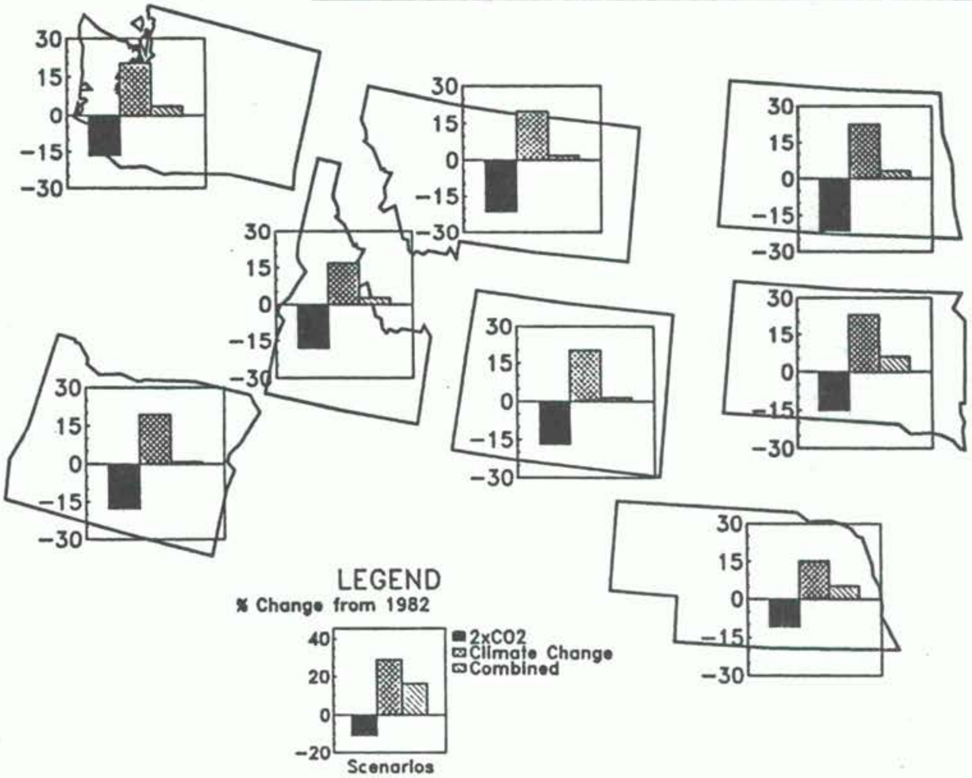


TABLE 3. Irrigated Crop Acreage Changes by Region by Scenario

PRODUCTION REGION	1982 BASE	CO$_2$ ONLY	CLIMATE CHANGE	COMBINED
	******** millions of acres ************			
Arizona	0.668	0.615	0.720	0.669
California	3.249	2.866	3.697	3.373
Corn Belt	0.764	0.667	0.894	0.807
Colorado	1.211	1.085	1.396	1.290
Delta States	3.246	2.671	2.841	2.898
Idaho	1.365	1.149	1.554	1.365
Kansas	2.330	2.035	2.229	2.156
Montana	0.442	0.364	0.507	0.445
Nebraska	5.070	4.648	5.697	5.478
North Dakota	0.089	0.077	0.108	0.098
New Mexico	0.337	0.308	0.375	0.346
Nevada	0.049	0.041	0.056	0.050
Oregon	0.324	0.272	0.372	0.327
Oklahoma	0.332	0.294	0.381	0.341
South Dakota	0.237	0.218	0.268	0.252
Southeast	0.563	0.521	0.646	0.605
Texas	3.374	3.025	3.720	3.504
Utah	0.199	0.164	0.227	0.202
Washington	0.623	0.525	0.728	0.650
Wyoming	0.203	0.167	0.235	0.209
TOTAL	24.675	21.712	26.651	25.065

Figure 7. Southwestern Irrigated Crop Acreage Changes

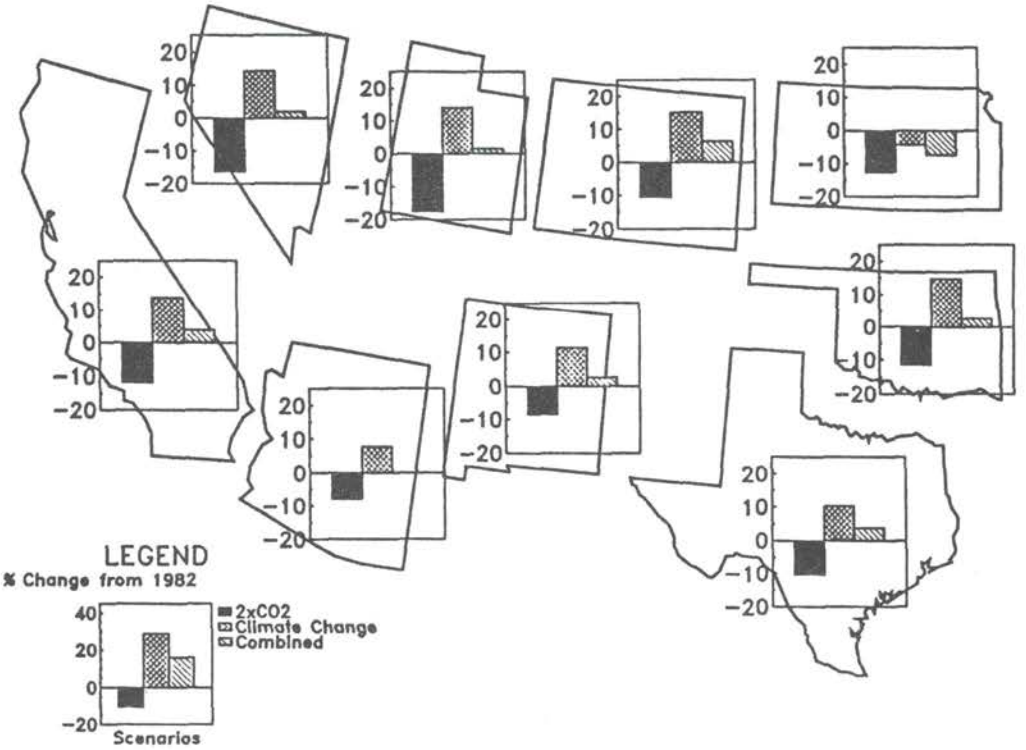
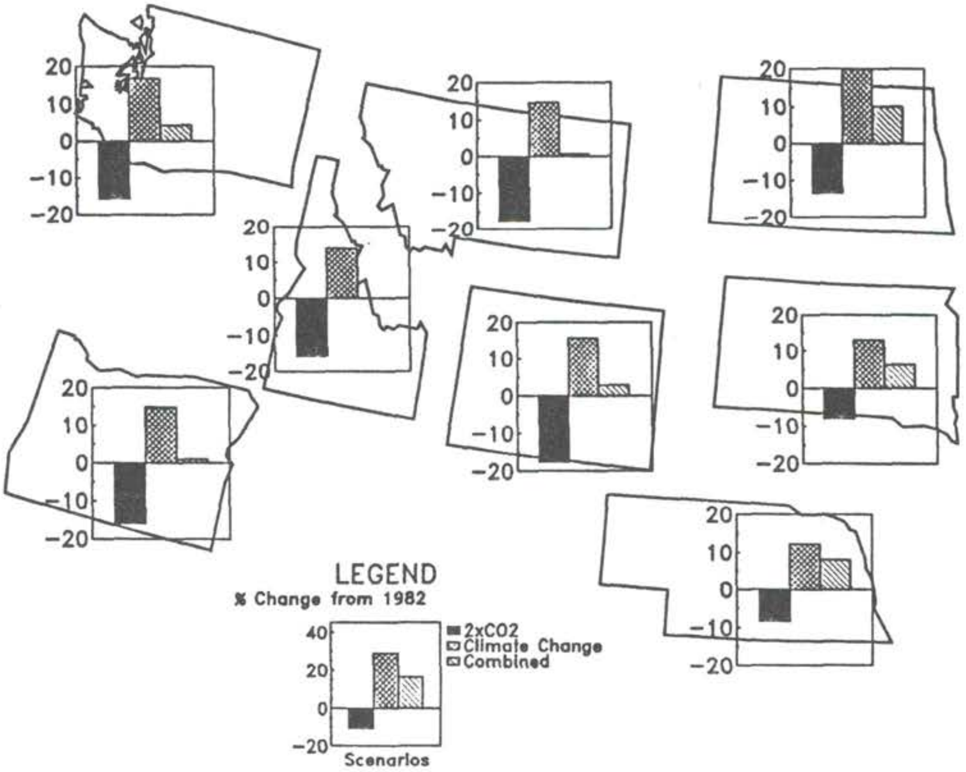


Figure 8. Northwestern Irrigated Crop Acreage Changes



and use? Table 4 lists the estimates of use for the base year and each of the scenarios. In the aggregate, these figures are in sharp contrast to the estimated acreage changes. These differences are due in large measure to the increases in evapotranspiration shown in Table 1. The CO_2 case results in a 12% reduction in irrigation water use. If only the climate change effects were analyzed, then irrigation water use would rise by 19.5%. The combined analysis of both sets of effects produces an 11.6% increase which is remarkably higher than the 1.6% underlying increase in irrigated acreage. In average per acre terms, applied water rates would rise from roughly 1.65 acre-feet per acre under the base and CO_2 scenarios to 1.82 acre-feet per acre for the climate change and combined cases.

Graphically and geographically, these changes are displayed in Figures 9 and 10. While for many of the preceding analyses the CO_2 and climate change effects seemed crudely balanced, they are clearly imbalanced when viewed in terms of the use of water resources. The climate change effects even when modulated by market forces clearly dominate the CO_2 enhancement. However, it must be emphasized that these results are based upon preliminary assessments of evapotranspiration changes and that no improvements in water use efficiency due to elevated CO_2 concentrations has been included. Each of these areas are active research topics. As these panels show, changes of 20% or more are not uncommon for many of the production regions. In a region already well-known for its strife over water, this magnitude of impact could be critical. At the least, it will stretch the capacity of water resource managers and perhaps cause us to rethink some of the archaic methods used to allocate water.

Water use and competition in the West are critical for environmental quality as well. Large segments of the national wild and scenic rivers system are in these affected regions. Can these investments survive this level of anticated increase in demand for irrigation water? Wildlife habitat is critically affected by agricultural operations both by the availability of riparian habitat as well as by the magnitue of water diversions. Finally, irrigation return flows, both surface and subsurface, are the conduit for many agrichemical and toxic residues. If the assumptions employed in this analysis are broadly correct, then we would expect one of the first manifestations of climate change impacts upon agriculture to be intensified water resource competition.

TABLE 4. Irrigation Water Use Changes by Region by Scenario

PRODUCTION REGION	1982 BASE	CO_2 ONLY	CLIMATE CHANGE	COMBINED
	******** millions of acre-feet *********			
Arizona	2.990	2.755	3.325	3.088
California	10.102	8.743	11.768	10.797
Corn Belt	0.522	0.456	0.703	0.631
Colorado	1.809	1.639	2.197	2.048
Delta States	5.061	4.103	5.062	5.062
Idaho	2.036	1.717	2.892	2.541
Kansas	3.038	2.697	3.139	3.139
Montana	0.591	0.489	0.833	0.731
Nebraska	5.304	4.872	6.286	6.080
North Dakota	0.083	0.071	0.119	0.107
New Mexico	0.626	0.575	0.729	0.676
Nevada	0.120	0.101	0.138	0.123
Oregon	0.561	0.475	0.721	0.635
Oklahoma	0.411	0.367	0.530	0.478
South Dakota	0.213	0.198	0.250	0.237
Southeast	0.335	0.312	0.458	0.432
Texas	4.970	4.507	6.769	6.297
Utah	0.385	0.318	0.456	0.405
Washington	1.178	1.011	1.625	1.465
Wyoming	0.408	0.334	0.547	0.485
TOTAL	40.743	35.740	48.547	45.457

Figure 9. Southwestern Irrigation Water Use Changes

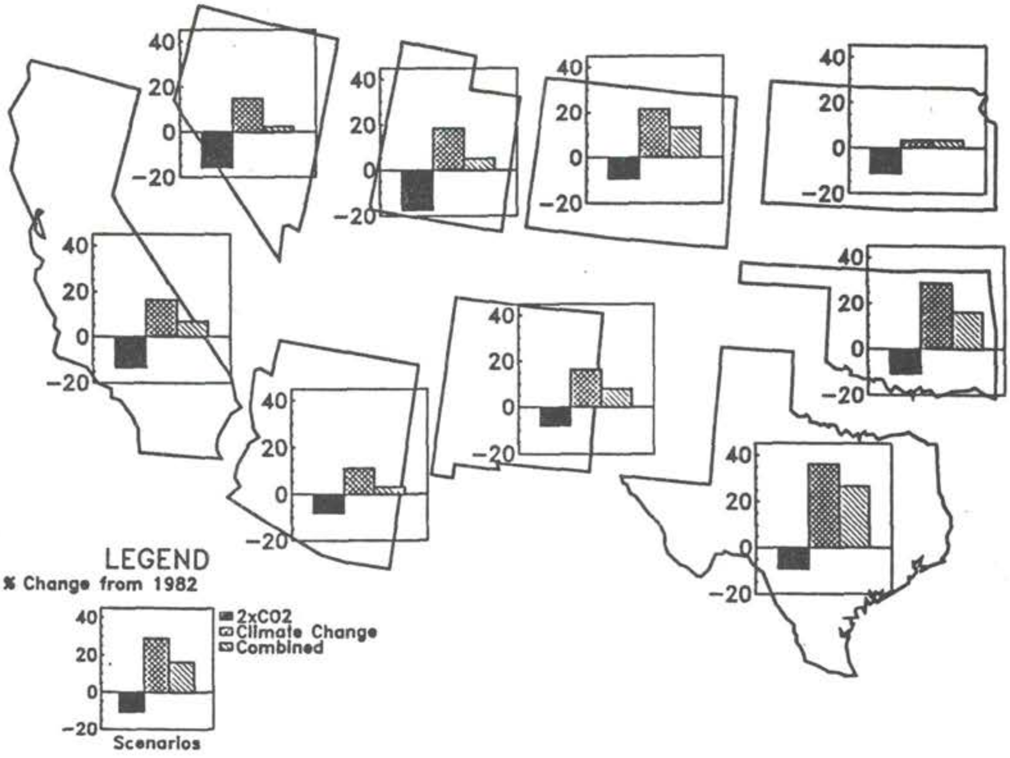
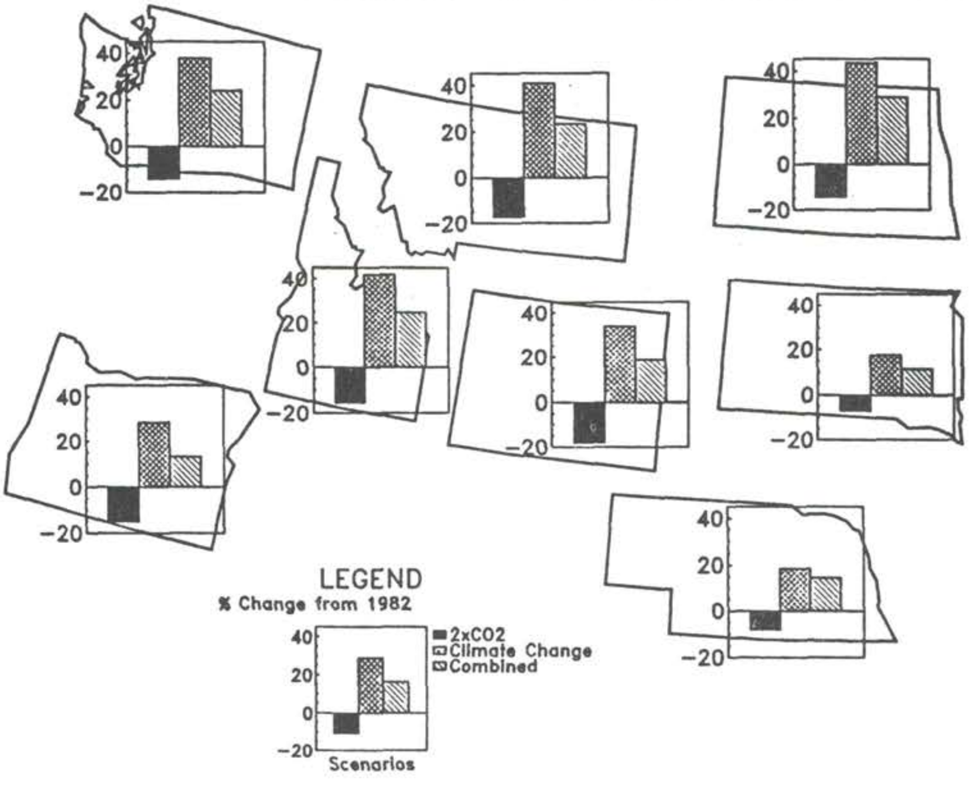


Figure 10. Northwestern Irrigation Water Use Changes



Conclusions

As indicated throughout, this research was intended to provide a broad estimate of the relative scope of climate change impacts upon agriculture. Defining a standard methodolgy for this assessment allows a greater focus on the assumptions employed rather than the methods. Several immediate research needs emerge. First, further refinements are needed in the specification of the impact of carbon dioxide concentration and climate changes upon individual crop productivities. In particular, these effects should be estimated with crop phenology models which include CO_2 enhancement. Similarly, while research has begun on the estimation of evapotranspirational changes, no scientific consensus exists. Even more urgent are improved regional precipitation and water supply impacts.

Not all improvements deal with the biologic response models. An important area of socio-economic inquiry is an investigation of the nature and costs of mitigating investments by individuals and society. One clear example that emerges form this research is changes in the institutional rules governing the allocation of water in many regions of the western United States. Water markets could be incorporated into national agricultural models to assess the impact of market forces upon resource allocation and use. These models could also introduce on-farm investment response to measure the trade-off between capital and improved irrigation efficiencies

At the macro level, we need to understand the future of agricultural programs with a particular view to subsidies and how changes in their design could provide offsetting forces. We require estimates of the effect of climate changes upon other important supply regions globally so as to evaluate possible changes in the size of the agricultural export market. Increased attention to the evaluation of changes in nonpoint source pollution loadings from agriculture as it adjusts in response to these global environmental changes is indicated. Lastly, we need to go beyond the simple aggregate arithmetic of national market outcomes to identify the types and direction of changes that are likely to be played out in response to climatic changes.

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STRATEGIES FOR ADAPTING AGRICULTURE TO ADAPT TO CLIMATE CHANGE

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This paper is adapted from a more detailed analysis of food security strategies contained in a recently published paper by Dr. Martin Rogoff and myself (Rogoff and Rawlins, 1987).

A little background on how we became involved in this subject may be helpful. In the early 80's Martin and I had responsibilities for strategic planning for the Agricultural Research Service, first in the area of agricultural energy and then for the Agency as a whole. As members of the National Program Staff Martin had responsibility for biotechnology and I directed the natural resources program. One of the items in the 1977 Farm Bill we wrestled with was the designation of USDA as the "lead food agency". Our interpretation of this was that USDA had the responsibility for the Nation's food security, just as the Department of Defense has responsibility of the Nation's military security.

Our analysis revealed serious deficiencies. The human food chain is vulnerable in the long term. Normally we store little food compared to annual consumption. Storage of food products is difficult and expensive. But without more storage the carrying capacity of the food system is determined by the output of its worst production year. The existing US food chain could collapse as a result of one Fall without a harvest.

The US food system is highly dependent on weather, on fossil energy, and on other non-renewable inputs. If future weather patterns fluctuate as they have in the past, or if replacements for depleting fossil energy reserves are not found in time, the probability of experiencing a serious shortfall in food production in the next few hundred years appears almost certain. Add to this the potential for increased variability in rainfall and increased temperature that could result from carbon dioxide-induced climate change and we increase the vulnerability of our present food system. Our present food system depends on the successful completion of the flowering, pollination and seed formation each year for a very limited set, less than a handful, of crop species. Martin and I reasoned that something as critical as the human food supply needed more resiliency than this. Without alternative means of food production we are totally unprepared to cope with emergencies that could result from such things as climate change.

ANALYSIS OF THE PROBLEM

The source of all food energy is the sun. Through the process of photosynthesis in green leaves carbon from the atmosphere is reduced and combined with other elements to form sugar, from which all biomass is produced. The potential food energy captured in the form of biomass each year is hundreds of times more than the human population can now use. But much of it is the form of lignocellulose, which humans cannot digest. Our diet is derived primarily from seeds and other plant storage organs, or from animals, some of which can digest the more abundant cellulosic components of biomass.

The fact that our diet consists largely of plant seeds and storage organs makes it heavily dependent on annual crops. Annual crops expose the soil to erosion by wind and water. The natural perennial climax plant species that covered the land before it was cleared for agriculture maintained a protective organic mulch covering the soil. Soil erosion depletes not only the soil nutrients, but the loss of soil depth reduces the soil's capacity to absorb and store water between rains, increasing its vulnerability to drought.

Because annual crops are not naturally suited to the ecosystems in which they are grown, they require high inputs of agrichemicals, nutrients and fuel to produce adequate yields and to make them competitive with natural species. These inputs are dependent upon finite reserves of fossil fuels. Both soil erosion and depletion of fossil fuel reserves limit the sustainability of a food system based largely on the production of annual crops.

Our proposed alternative is based on the production of food from cellulose produced by wide range of perennial plant species that are adapted to natural ecosystems. A new crop, Kenaf, is one possibility, but tulip poplar or whatever fits the ecosystem best would be the crop of choice. The cellulose stored in these perennial plants represents a living reserve of feedstock for the food system that costs nothing to store. It need be harvested only when the demand for it exists. Producing food from the biomass of perennial species substantially increases the carrying capacity and sustainability of the food system. Its carrying capacity is increased in two ways; (1) by converting a much larger fraction of the annual solar energy flux captured in the form of biomass into human food, and (2) by eliminating the dependency of the food system on annual production. Its sustainability is increased by replacing annual crop species with perennial climax species that are more suited to the natural ecosystem, are less dependent on high inputs of fuel and chemicals from finite fossil fuel reserves, and which subject the soil to less erosion.

Producing food from lignocellulose consists of the following processes:

1. Biotechnological or chemical conversion to simple sugars for transportation as syrups to food production sites.

2. Chemical and biotechnological conversion of simple sugars to food or animal feed components, or to edible plant (or animal) organs in vitro at food consumption sites.

3. Conversion of food components to edible products as appropriate.

The basic strategy is to separate the set of processes concerned with carbon reduction, biomass synthesis and storage, which must be carried out in sunlight, from those concerned with the conversion of stored carbon into food, which don't require sunlight. Only this first set of processes is seasonally dependent. The second set, the conversion of stored polymers to simple sugar syrups at "the farm" site, transport and conversion of the syrups to food in "factories" near major population centers, can continue year round as dictated by demand.

We envision the same biological growth and biosynthetic processes that now convert photosynthate and polymers into food products in crop plants to be used to convert sugars into food products in food factories. The difference lies in the selectivity of the food factory processes to produce only edible material, as opposed to simultaneous biosynthesis of both edible and inedible plant parts by conventional crops.

Space does not permit a detailed outline of the conversion process here, but technically there appear to be no insurmountable barriers. The same biotechnology that is being pursued to enhance the productivity of crop plants in the field can be applied to enhance the growth of specific plant organs on sugar-based growth media indoors.

Let's take a look at what impact this alternative food system would have on the food we eat. First, grazing animals certainly would remain part of the system. These animals harvest and convert to human food a large amount of biomass that is too sparsely distributed to be feasibly harvested by other means. The increased dependence of the food system on natural ecosystems should enlarge the area available for grazing. Integrated forest livestock systems are already being used in many areas of the country. Wildlife and game production could also be enhanced by limited reforestation of some of our farm lands. (Reversing the deforestation trend by placing crop land back into perennial species would also provide a sink for atmospheric carbon dioxide.)

Chemical conversion of sugar to starch and other carbohydrate products could immediately provide feed for animals. Fish are very efficient converters of feed into food, and will be part of the biotechnical conversion process. The fact that the major portion of US agricultural land, most of the corn and soybeans, is devoted to the production of animal feed makes direct chemical conversion of sugar from biomass into animal feed a major contributor toward decreasing the demand for annual crops. Of course a sizeable fraction of the biomass could be harvested as forage to serve as a direct source of animal feed without first reducing it to sugar.

Poultry is also an efficient converter of feed to food, and can, like hogs, make use of waste products such as fish meal. Animals will be always be important in converting wastes to human food. A very large fraction of our existing food supply ends up as food waste that could be easily converted to food through animals if we developed the systems to recycle it.

No technological barriers seem to exist for developing products such as flour for bread or pasta, or a substitute for mashed potatoes directly from sugar. Specific proteins are now being produced in microbiological reactors, which could be used to supplement the diet. Since carbohydrate products are the backbone of the human food supply, it would appear that, combined with abundant animal products, a base food supply could be relatively easily achieved.

But ultimately we want more than meat and potatoes. Exciting new biotechnology is giving us the tools to produce specific plant organs indoors on culture media. Much of this effort is being devoted to cell culture to develop whole living plants from a single cell. But recent research is developing the capability to grow just part of the plant the same way. In one case cotton fibers are being grown without the rest of the cotton plant. Cherry fruit tissue has also been grown in a similar way. Other such products are waiting in the wings.

EXPLANATION OF KEY STRATEGIES

1. Primary plants grown in soil will be perennial, not annual.

Limiting plant production in soil to perennial field crops grown primarily in rainfed geographic areas has several major benefits. Soil will suffer less erosion; and both water and fossil energy will be spared by reducing the need for irrigation. With cellulosic materials comprising the major end product of soil based agriculture, living perennials can serve as an easily stored reserve of feedstocks. The fact that several year's supply of feedstock might exist in this reserve permits long-term contingency planning. Projected increases in food demand can be met simply by gradually expanding the area of this standing crop resource. In short, the annual yield of photosynthate can be stored, or harvested, as required. Non-crop cellulosic materials, previously useless as food other than through biotransformation by animals, become an emergency sump of reduced carbon for human food use. A hypothetical perennial hybrid with the attributes of tulip poplar, kenaf, and a nitrogen-fixing symbiont can be envisioned as the field crop of choice.

2. Bioconversion of standing stocks of reduced carbon to simple sugars with syrups as the main commodity produced from soil-based agriculture.

Processing of lignocellulose at the point of production allows by-products to be efficiently utilized. Practically everything, including the lignin, will either go into the conversion products or be used as fuel or fertilizer. "The farm" will be the primary point of food inventory control.

Only syrups will be transported to, and stored at, food production sites. In the existing system "food" moves into long-distance transportation channels involving refrigeration, cooling, controlled atmospheres, or other measures to protect it from spoilage. Technically the simplest means to move syrups is by pipeline. This is a low energy means of transport which requires no special steps for preservation at usual syrup concentrations. A demand-driven, year round harvest mode becomes possible. Syrup storage facilities at the food production site would only need capacity to balance minor fluctuations in supply and demand. Our present food system is supply-driven. Storage facilities must be large enough to carry the system from one harvest to the next. Year-round operations should significantly reduce the total size of unit processes including storage facilities, thus reducing overall capital investment. There will be no off seasons.

The primary source of energy for our food production facilities is natural sunlight captured on the farm and now converted to a sugar syrup stream. Waste disposal at the food production sites should be minimal since only edible plant parts, not whole plants, will be produced there.

Our scenario could significantly reduce the bulk of the existing system's current costs and problems. A spatially and temporally shortened marketing chain would reduce stored-product losses to pests, perhaps eliminating many of them. Also reduced or eliminated would be the cost for storage of raw food as mature or immature plant organs, e.g., seeds or seedbearing organs; long-term storage, e.g., freezing for raw or processed plant organs or parts; preservation processing, e.g., canning; packaging for long-term storage or long-distance transport; and processing of unripe harvested produce in transit or storage to ripen for market.

Food production in our alternative scenario is on-demand at demographically determined production sites in multipurpose facilities controlled by inventory-based systematics. Existing multipurpose, multisynthesis bioconversion or fermentation plants would seem to be reasonable models for these future systems.

3. Requiring only cellulose-rich plants for soil-based production, the alternate technology becomes relatively independent of climatic factors.

Barring cataclysmic continental natural disaster, e.g., nuclear winter, global axis shifts or total desertification, supply of cellulose is virtually assured. Even in extreme climates perennial floras can flourish. Localized early or late freezes, intermittent dry spells or excessive rainfall, may have disastrous effects on cropping systems whose products are annual plant organs or parts. Their effects on perennial crops grown for lignocellulose should be reversible by a following favorable season. Shifts in production loci, aside from social impacts, will simply shorten or lengthen syrup supply lines. Additional insurance the alternate technology provides is the potential of converting any cellulosic material to food, whether grown for the purpose or not.

POSSIBLE CONSTRAINTS

Assuming that the technologies we have envisioned are technically feasible, what other factors might stand in the way of achieving a secure food supply with this scenario? Four potential constraints are readily apparent; these are biomass availability, energy dependency, processing and delivery costs, and consumer acceptability of "high tech food".

1. Biomass Availability.

The alternate scenario proposes to reduce the dependency of food production on nonrenewable, resource-intensive agricultural production practices. This assumes that existing cellulose production capacity is adequate to generate the sugar feedstocks required for food. It is beyond this article's scope to analyze for preferred sites for biomass production under resource-conserving conditions. However, it is relatively simple to demonstrate that biomass availability will not prove to be a constraint.

Recent data indicate that the United States currently generates about 3.6 trillion pounds dry weight per annum of available lignocellulosic material, not counting that which ends up in agricultural end products. The available material includes wood chips, cereal straw, and cornstalks. Food consumption of major commodities in pounds retail weight for a 237 million population is 0.30 trillion pounds per annum. Two-thirds of this weight is made of high water-content products such as milk, meat, fruits, and vegetables. The other third includes grain, sugar, corn sweeteners and fats. Calculated annual US food consumption on a dry weight basis is, therefore, approximately 0.10 trillion pounds. On the basis of these numbers, the alternate food production technologies would required only 2.8 percent conversion efficiency of unused lignocellulose, or 7 percent conversion efficiency for its cellulose to provide all food consumed by the US population.

Use of these figures implies, correctly, that entry of the new technologies is foreseen as evolutionary, and that soil-based agriculture will continue at some level. Common sense, and the certain knowledge of consumer demand for specific "farm-produced" products dictate this assumption. The point, however, is that with current agricultural production providing over 30 times the necessary reduced carbon as waste, the acreage required for purposeful cellulose production is foreseen as relatively low. Conversion of only a small part of our highly productive agricultural land to the production of biomass would more than assure an adequate supply of food for the present population, leaving substantial arable reserve capacity for future population expansion. In short the feedstocks required should be renewable as long as energy flow from the sun is sufficient to maintain the carbon cycle.

2. Energy Dependency.

No quantitative energy analysis can be made for processes that do not exist. We can take a look in a general way at the energy budget of the current food system to see whether the new concepts provide any energy "surprises" which would negate its feasibility in terms of fossil fuel depletion.

It is abundantly clear that no one can convincingly argue that the existing food system can outlast our fossil fuel reserves. Our only hope for long term survival is to develop a food system substantially less dependent on fossil fuels.

The food system we have proposed is not radical in energy terms. We neither expect to create a new source of food energy, nor do we postulate a substitute for fossil fuel energy for success of our alternate food system.

What we propose to do is simply cycle a larger fraction of the annual carbon budget already being fixed in the leaves of growing plants through the human food chain. It appears that this fraction can be substantially increased, by at lease an order of magnitude. This eliminates the need to pour even more fossil energy into intensive annual crop culture to meet growing demand for food. The fixed carbon now wasted is largely recycled through microbial decomposition of organic residues. Routing a larger fraction of it through the human food chain would greatly relieve the pressure on the food system, and not perturb the balance of nature.

Even more important is the fact that our proposed scenario can reduce the currently high energy expenditure during food transfer and storage. The living reserve of standing perennial vegetation would cost little to maintain, and its potentially massive storage capacity would substantially raise the carrying capacity of the food system by removing the minimum year production limitation. It is the carrying capacity of the system that limits food security.

3. Economic Feasibility.

Traditional economic analysis is not very useful for long-term security issues, because no cost factors for a time 100 or more years from now can be projected realistically. One way to look at future economic feasibility is by comparison with the current food cost distribution at consumer level. The alternate technology cost distribution will be significantly different. By listing the estimated unit costs for the present system we can look at alternate technology unit operations, and project whether each new unit process could bear more or less cost. These unit costs are broadly divided into two operational categories, Farm Value and Market Bill. The latter represents the difference between payments to farmers for foodstuffs and consumer expenditures for these foods at food stores and eating places. It represented 72 cents of the consumer food dollar in 1982.

Analyses imply that reduced costs in the overall system could balance a sizeable increase in costs now incurred beyond the farm gate. Even if biotechnological food processing costs were to increase to double that in the present system, they imply that food cost to the consumer may not change.

What may be more important, however, is that whatever future comes to pass, whether extension of existing technology to 100-acre controlled environment domes, or the alternate technology, a massive infusion of new capital will be required. But new capital is scarce in the current food production, processing and distribution sectors. How to meet future capital demands needs to be a key issue in the future economic dialogue. Hopefully this time it will revolve around return on investment, not primarily on operating costs of production, as it has in the past. In short, there is little sense in agonizing over "economic feasibility" of new technology, when future parameters will actually control the costs.

4. Consumer Acceptability of New Technology Foods.

We do not propose to force future consumers to accept the next generation of ersatz coffee, and sawdust or algal bread. It is expected that plant growth in vitro will be held to the same quality standards as their current counterparts. We would even go so far as to project that certain products, e.g. soft drinks or preserves, which now rely on artificial flavorings, will be of better quality if prepared from plant tissues grown in vitro. We should detect no changes in our ketchup.

The challenge lies in developing technology to prepare high quality foods from singly-produced food components. Today we include textured soy proteins in certain foods, but the vegetarian veal cutlet has never generated broad consumer demand. This is due in part to the fact that consumers who want meat,want meat, but there is also a quality factor involved.

We do not deem the technical problem as insurmountable. There is great deal of research today attempting to define the basic determinants of food flavor and texture at the molecular level, and to determine the biochemical pathways involved in their formation. This applies to animal as well as plant-derived food products. For example, there is interest in overcoming the problem of "warmed-over flavor" in cooked beef, and "warmed-over texture" in pork. This is essential considering that single components of animal products should be no more difficult to produce biotechnologically than those from plant products. It is possible that culture of animal organs in vitro may require less time to attain than plant organs, since there is more basic knowledge of animal biochemistry and physiology than there is for plants.

There is even research emphasis now on unraveling the gustatory perception of smell. Success there would make an enormous contribution to the technology of fabricated foods.

We believe that significant inroads can be made initially by the new technologies, as they emerge, in the preparation of the carbohydrate polymer foods. One can readily visualize acceptable starchy foods in the pasta, bread and various dessert categories. Sauces are now fabricated products in this category. Dairy products would also appear a tempting target for these technologies.t There is no intent to stretch the technology's potential. We simply wish to point out that we believe the major diet items can be replaced by items produced by the new technologies without sacrifice of quality. It is the major diet items, primarily carbohydrates, on which food security is based. The condiments are trivia.

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HOW CLIMATE CHANGE IN THE GREAT LAKES REGION MAY AFFECT ENERGY, HYDROLOGY, SHIPPING AND RECREATION

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I. PROLOGUE

This discussion is about possibilities. It is not about forecasts. It is not a doomsday warning. It is an attempt to answer some questions, but also to raise awareness of an issue that will soon confront resource managers, decisionmakers and others with interests in the Great Lakes region. The issue is the potential impact of future climate warming on water resources and dependent activities.

The Great Lakes contains the world's largest system of fresh water lakes (Figure 1). It is an international basin, home to 28 million people in the United States and 8 million in Canada. Approximately 75% of them rely on the lakes for drinking water. The basin is also highly industrialized and is a major producer of crops and wood products. Its water resources are exploited for hydroelectric power production, commercial shipping and industrial processing, particularly steel production. However, these water users must share the resource with fishing, recreation and tourism industries. For example, in the United States alone, these industries have annually generated between US$8 and US$12 billion.

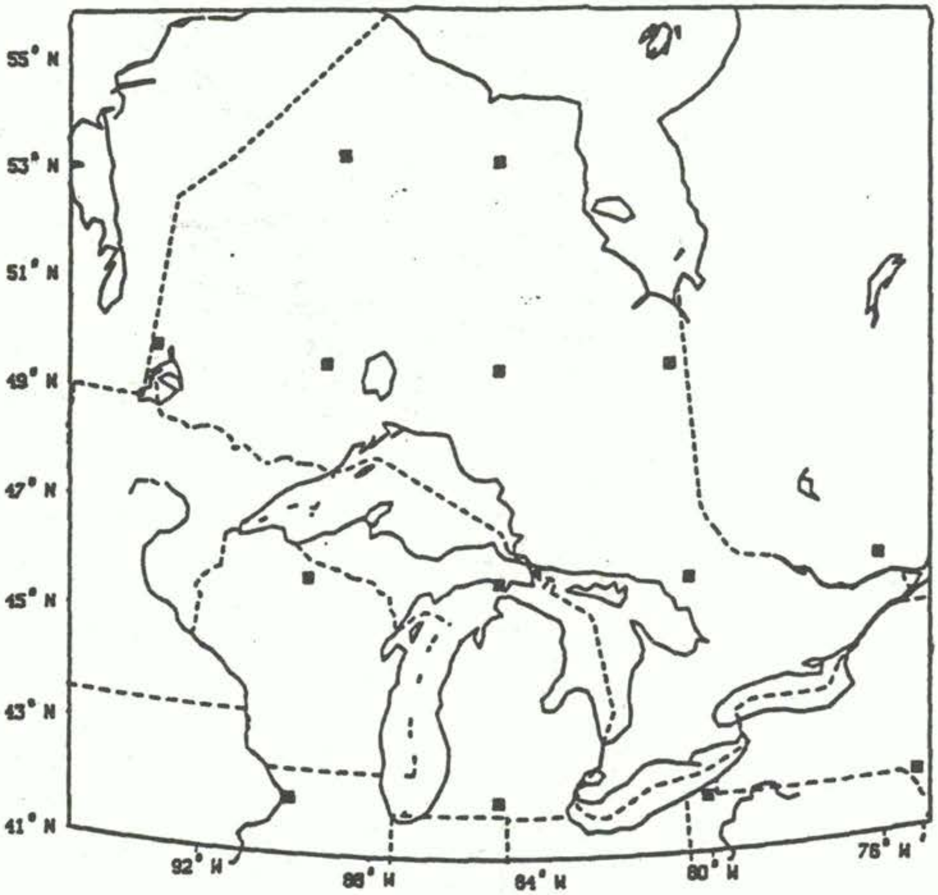


Figure 1: The Province of Ontario, Canada, including the Great Lakes. Grid points, 4 degrees x 5 degrees, were interpolated from the GISS general circulation model's output of 8 degree x 10 degree grid squares (see Cohen, 1986).

Some of the activities described above are tied directly to the lakes themselves (e.g. shipping). Others, such as winter recreation, are not dependent on the lakes' water supplies directly, but are sensitive to variations in climate. In addition, certain climate sensitive activities, such as agriculture, have the potential to become major consumers of water, so variations in climate that affect water demand could indirectly affect lake levels.

In this paper, there is a review of a pilot study of the Ontario portion of the Great Lakes region. This study was initiated by Environment Canada in 1984, and included participants from the Canadian government, universities and the private sector. It was an attempt to quantify the impacts of a scenario of climate warming on a wide range of activities, including hydroelectric power production, commercial shipping, recreation and agriculture. This study is presented with the hope that it will encourage more active consideration of climate impacts from a broader range of individuals and agencies with interests in the region.

II. REGIONAL IMPACTS OF CLIMATE CHANGE: THEORIES AND UNCERTAINTIES

Water resources in any region of the world are influenced by a number of environmental factors. One of these factors, climate, is a highly variable component of nature. In recent centuries and decades, seasonal and interannual climate variations have resulted in short-term extreme events such as droughts and floods, longer-term fluctuations in streamflows and lake levels, and changes in snowpack and ice cover. These extreme events and long-term changes have had significant impacts on society, including economic fluctuations, property damage, and loss of life. Consequently, the assessment of climate impacts on water resources involves not only climatology and hydrology, but many other disciplines as well, including the social sciences, engineering, biological sciences, and economics.

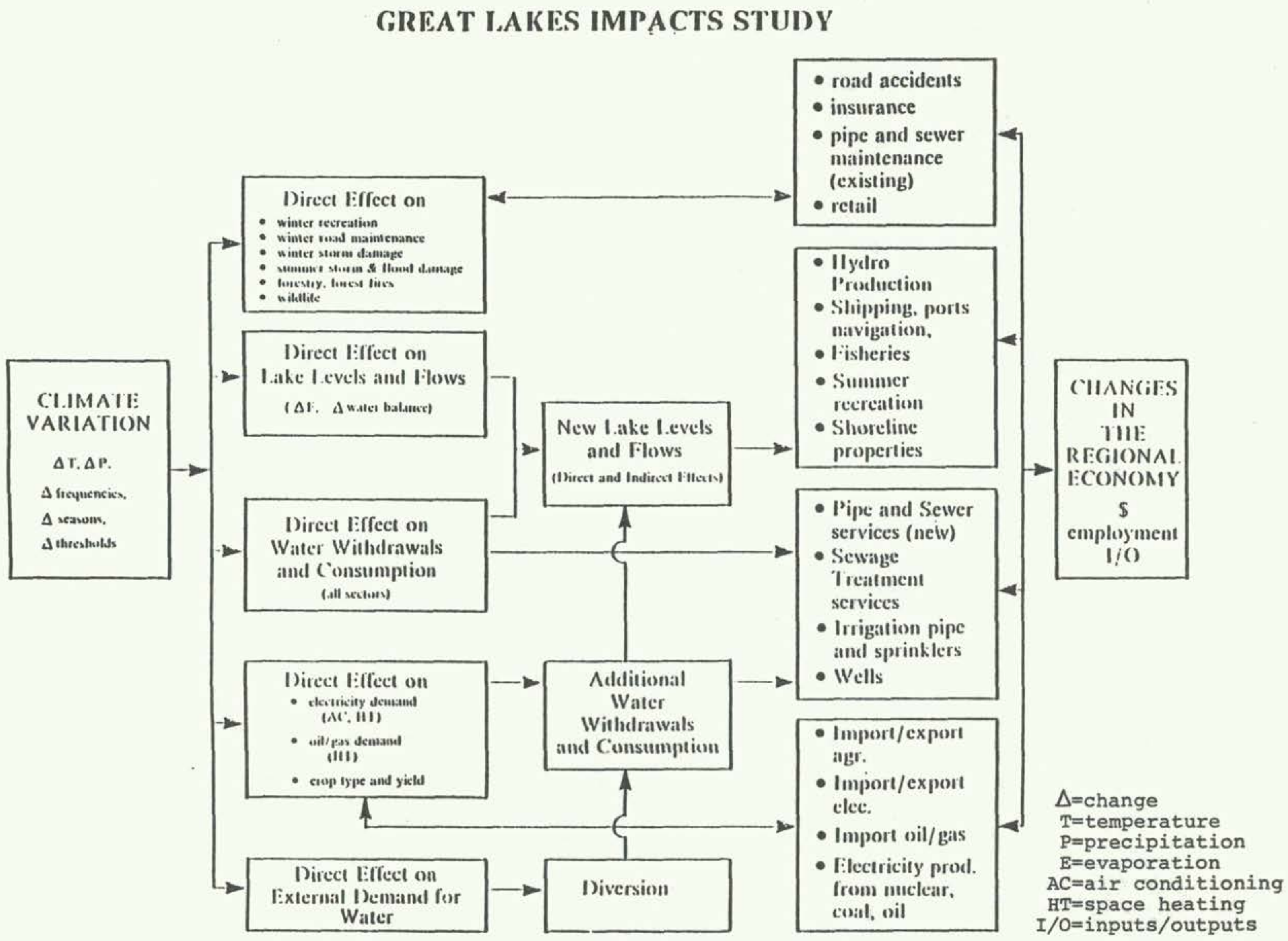
The past can teach us a great deal about how climate, water resources, and society interact. However, projections of the future must include a new element, not experienced by previous generations. That element is the so-called "Greenhouse Effect," a possible warming of the earth's climate due to continuous increases in atmospheric concentrations of carbon dioxide and other trace gases (WMO, 1986). There is considerable uncertainty regarding many aspects of the projected warming, but the possible magnitude of this change to the global environment could lead to changes in the hydrological cycle that would be too great to ignore. Such changes could affect water resources planning and management in many regions.

A model framework of linkages between climate, water supplies (or Net Basin Supplies, NBS), lake levels, and the Great Lakes region's economy is presented in Figure 2. Starting from the left side of the figure, a variation in climate is identified either by a change to a new mean condition (e.g., warmer temperatures), or by changes in frequencies of extreme events, lengths of season, or the exceedance of critical thresholds (e.g., temperatures below zero Centigrade). This variation can directly influence land-based activities, basin hydrology, regional water demand, energy demand for heating and air conditioning, and perhaps, demand for exports and imports of various commodities, including water. Changes in water demand could alter lake levels and NBS, and lead to changes in water distribution services. The new lake levels and streamflows could also affect several water-based activities, including hydroelectric power production and commercial shipping.

Before discussing the results of the pilot study, it is appropriate to outline four major uncertainties that confronted the study team:

- projections of future climate at the regional scale
- mismatch of scales
- linkages with climate change, and
- projections of non-climate factors

Climate modelling and projections of global greenhouse warming involve many uncertainties. General Circulation Models (GCM) are not yet able to precisely reproduce the present pattern of climate. When various GCMs are used to project the Greenhouse Effect climate, the models' results for temperatures are similar on a global scale, but there are large differences in projected global precipitation between the models. There are also large differences in temperature and precipitation projections at individual grid points, and the models' coarse resolution prevents them from providing detailed regional information. In the pilot study, it was necessary to adapt these global scale outputs by utilizing present data from existing climate stations, rather than the models' estimates of present climate. Model projected climate changes were then added to the station values to produce regional scale scenarios of future climate.



Δ=change
T=temperature
P=precipitation
E=evaporation
AC=air conditioning
HT=space heating
I/O=inputs/outputs

Figure 2
Interconnected components of climate impacts and societal responses within the Great Lakes region. (Cohen, 1986)

The mismatch of scales problem refers to fundamental differences between the temporal and spatial scales of global climate warming, and changes in the regional economy and environment. The response time of forests to climate change may be close to the same rate as the projected Greenhouse warming, while crops and watersheds would probably respond at a much faster rate. Human response to climate change in pre-industrial times was often abandonment of sites and migration to new sites with more favourable climate. Modern societies have responded to change with a mixture of technological and institutional approaches. Future generations may respond in similar fashion, depending on prevailing economic and political considerations. Is it possible to project what these future responses might be? This leads us to the issue of linkages between climate and society.

The main focus of the recent climate change debate has been the accuracy of climate projections. However, even if we had completely reliable projections, could we then quantitatively determine what the impacts would be? For instance, what would happen to electricity supplies and demand? Would the side effects on energy prices and employment be positive or negative? How would trade patterns be altered? Traditionally, researchers in energy, economics and many other disciplines have implicitly considered climate to be a constant element in their modelling. Now, climatologists are telling them that climate is a <u>variable</u> element. Is it possible to use economic models to determine the impacts of climate change on a region? Do we really know enough about climate-society linkages to be able to do this?

Finally, we have to recognize that when projections of future impacts are made, they are generally done with the assumption that non-climate factors do not change from present conditions. This allows us to determine what the impacts might be if society chooses to maintain the status quo. Unfortunately, nobody really knows how future technologies and political alliances will change; yet it is highly probable that these and other changes will alter regional and global climate-society linkages.

What this pilot study attempted to do was to indicate the potential direction, and if possible the magnitude of impacts in the Great Lakes region. The study was unique because of its breadth, and because it was probably the first study of a region's economy to utilize as input, a climate scenario derived from a GCM. The study was incomplete in some ways, but there were a number of preliminary results. These are reported below.

III. IMPACTS OF A SCENARIO OF CLIMATE CHANGE

A. Climate Scenario

The pilot study used a scenario derived from the Goddard Institute for Space Studies (GISS) model projection of Greenhouse warming (Hansen et al., 1983). In the Great Lakes, this scenario indicated an annual temperature increase of 4.3 - 4.8 degrees Centigrade. Winter would be 5.1 - 5.9 degrees Centigrade warmer, while summer temperatures would increase by 2.8 - 4.3 degrees Centigrade. Annual precipitation would increase by 6.5%, though the southern half of the region would experience reduced precipitation during late summer and autumn (Cohen, 1986).

B. Hydrology

Due to uncertainties regarding future changes in humidity, lake surface temperatures and other regional scale parameters, it is difficult to be very precise about the magnitude of hydrologic changes. However, a recent study of 140 scenarios (Cohen, 1987a) derived from GCMs, historical data and hypothetical cases, indicates that in a majority of scenarios, the higher temperatures would lead to great evapotranspiration losses. These losses would probably overshadow projected gains in precipitation. Consequently, in a majority of scenarios, water supplies (or Net Basin Supplies, NBS) are projected to decrease. This would result in lower average annual lake levels and streamflow. In an earlier study, Bruce (1984) had reached similar conclusions. Studies have also been conducted by the U.S. National Oceanic and Atmospheric Administration. Results of these are discussed by Frank Quinn elsewhere in this volume.

Calculations using the GISS scenario, with assumed present normal wind and humidity, indicated the same result as the majority, i.e., lower supplies, streamflow and lake levels. The projected reduction in annual NBS was 15% below the long term average (Southam and Dumont, 1985). If consumptive use of water increases, the reduction would be greater. Even if consumptive use was to remain at present rates, average lake levels would be similar to the low levels experienced in 1963-1965, which were the lowest this century at Lakes Michigan and Huron.

C. Energy

The energy supply study focused on four generating stations operated by Ontario Hydro (University of Windsor, 1986). Results showed that the projected reduction in water supplies would lead to annual losses of 2200-4200 GWh, depending on how Lake Ontario outflows are regulated. This is equivalent to CAN$34 to CAN$65 million (based on 1979 data). When compared to current (1979) annual fuel (nuclear, coal) and administration costs, which total CAN$1200 million, these annual losses are equivalent to 3-6%. Total annual electricity demand would decline in this scenario because of lower demand for space heating. Demand for summer air conditioning would increase because of the warmer temperatures. The magnitude of this increase is difficult to determine, because of uncertainties in projecting the number of customers with air conditioning units, but it appears that the increase would be smaller than the change in winter demand. Overall, total annual electricity demand would experience a net decrease of 6400-7600 GWh below Ontario Hydro's energy demand <u>forecasts</u>, a 2-3% reduction. This would facilitate a decrease in the amount of energy generated by more expensive coal and nuclear power, resulting in an annual savings of CAN$99 to CAN$118 million (1979$).

When the two results are combined, the net effect is a saving of CAN$34 to CAN$54 million annual to Ontario Hydro. However, there are uncertainties in quantifying present climate-energy demand linkages, and future linkages are bound to be affected by external factors (energy price, technological change, etc.).

D. Commercial Shipping

In this scenario, lake levels are lower, but the lakes are virtually ice-free because of the warmer temperatures. A study of the principal dry bulk commodities (iron ore, limestone, coal, grain) was undertaken to see what the net effect might be (University of Windsor, 1986). Ice cover affects the length of the shipping season, so a warmer climate means a longer season. However, the lower lake levels mean reduced depths at channels and locks, thereby reducing cargo capacities per voyage.

Results showed that annual navigation costs would increase by US$10 to US$12 million. In a scenario of increased coal tonnage (a side effect of reduced hydroelectric power production), losses would be greater since most coal shipments are inter-lake, requiring ships to travel through the shallowest points in the basin.

The largest overall losses, US$27.8 million, would be incurred if the region would experience the GISS scenario climate, increased coal tonnage and increased consumptive use (which further lowers lake levels). Compared to projected "normal climate" shipping costs of US$234.3 (1979 data), these losses are equivalent to 11.9%.

E. Tourism and Recreation

Eight Ontario parks were studied to determine the impacts of climate warming on camping expenditures (Wall et al., 1985). It was assumed that camper traffic would change proportionally with changes in the length of season, defined using temperature only. Economic multipliers were used to calculate the impacts in regions surrounding each park. Results showed that expenditures would increase by approximately CAN$4 million, mostly for food, accommodation and transportation. The increases at the various parks ranged from 28-44%.

Two ski resorts, one each southern and northern Ontario, were chosen for a study of downhill skiing (Wall et al., 1985). As above, the key element was climate-induced changes in the length of the season. In this case, a snow cover study had to be undertaken. Results showed that the average ski season at the northern site would be reduced from 131 days down to 80 days. Using survey estimates of local skier expenditures, this translates into a loss of approximately CAN$2 million, though this could be mitigated by artificial snowmaking. The southern site, located east of Lake Huron, would experience a complete disappearance of reliable snow cover, resulting in a loss of CAN$36.5 million for the area's resorts, and a CAN$12.8 million loss for the retail and service trade in the nearby town of Collingwood.

There are many questions regarding potential spin-offs that could be asked. For instance, how would winter tourism patterns change? How would southern Ontario resorts adapt? What are the implications for the U.S. side of the basin? Would the longer summer season lead to increased pressure for development along the shorelines of the Great Lakes, as well as the smaller lakes within the region?

F. Other Studies

A study of Ontario agriculture was conducted as part of this effort (Smit, 1987). Detailed discussion is provided by Barry Smit elsewhere in this volume. Although benefits would be derived from expansion of production into available sites in higher latitudes, the overall result indicates a 7% reduction in Ontario's productive capacity because of the increase in summer moisture stress resulting from higher summer temperatures. One solution to this would be to increase the availability of irrigation. However, there are indications that the consumptive use of Great Lakes water is already on the increase because of urbanization, industrialization and increased demands for electric power from non-hydro sources (IJC, 1985). Further, a study of municipal water use suggested that a 2.6% increase in annual demand (for lawn watering, golf courses, etc.) could occur due to climate warming (Cohen, 1987b). The question is, could increased demand for irrigation water be accommodated in a scenario of higher industrial and municipal demands, continued in-situ demands (e.g., shipping) and lower regional water supplies?

IV. NEW QUESTIONS--WHO WILL ANSWER THEM?

The pilot study described herein provided an opportunity to assess the applicability and capability of current available methods to delineate, to some degree, possible impacts of a climate warming scenario. It also enabled the participants to gain experience as impacts researchers, and to respond in a reasonable manner to requests for information coming from a number of policy advisory groups (e.g., International Joint Commission).

Many questions need to be answered. Some of these pertain to the climate projections themselves, but we must not get distracted by the finer details of that particular issue. Interested stakeholders, including researchers, policy advisors and decisionmakers, can participate in the debate only if they know what climate data they need to do impacts or policy studies. What is needed is a broader base of impacts research and researchers from a wide range of disciplines, so that climate-environment and climate-society linkages can be modelled better. Otherwise, we will never be able to fully answer the impacts questions, even if climate projections become more accurate.

Active collaboration between scientists and policymakers has been advocated by leading scientists, despite the uncertainties in climate modelling (WMO, 1986). This conference represents an important step in facilitating this collaboration. Another step will be taken in 1988, when a workshop on Great Lakes impacts will be held. This workshop is being organized by the U.S. and Canadian Climate Program Offices, and the U.S. Environmental Protection Agency. Hopefully, it will facilitate communication and collaboration among a broad range of individuals and organizations, and will ultimately lead to a better understanding of the potential impacts of future climate warming in the Great Lakes region.

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LIKELY EFFECTS OF CLIMATE CHANGE ON AGRICULTURE IN THE GREAT LAKES REGION

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on Preparing for Climate Change: A Co-operative Approach
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INTRODUCTION

Recent studies have indicated that the earth might experience profound shifts in climate conditions over the next 30-100 years due to increasing concentrations of CO_2 and other 'greenhouse gases' in the atmosphere. This has prompted analysts to speculate on the extent to which these changes in climate might ultimately affect the structure of society. These assessments of the interactions between climate change and socio-economic structure are especially relevant to the agri-food sector where primary production is to a large degree dependent upon climate.

This paper reports on findings from a study of the potential implications of climate change for the agri-food sector in Ontario, Canada. The study represents one of several examing the impacts of climate change in the Great Lakes' region. The general conclusions regarding sensitivities of agriculture to climate change have obvious pertinence to other jurisdictions in the Great Lakes' area, particularly the states of Wisconsin, Michigan and New York. The study is described in the Environment Canada publication Climate Change Digest, No. CCD 87-02.

The study is designed to gauge the sensitivity of various aspects of agriculture to the specified changes in climate conditions, rather than predict or forecast the effects of climate change on the agri-food sector.

CLIMATE CHANGE SCENARIOS

Two scenarios for climate change associated with an increase in atmospheric concentrations of CO_2 are used. Scenario A is based upon a model developed by the Geophysical Fluid Dynamics Laboratory, whereas Scenario B employs output from a similar analysis by the Goddard Institute of Space Studies. The direction of the changes are generally consistent across the two scenarios of climate change, although the magnitude varies.

EFFECTS ON CLIMATE RESOURCES FOR CROP PRODUCTION

The study estimates the long-term normal climate conditions expected under each of the scenarios. The conditions analyzed are those which influence crop yields, such as temperature, growing season length, cloud cover, precipitation and potential evapotranspiration.

The Climate Change Scenarios are characterized by considerable increases in temperature and precipitation over current levels throughout the study area. Increases in the length of the growing season would range from 35 days to 60 days. The growing season in northern agricultural areas would be similar to the current growing season in the southerly parts of the province. Growing season length would increase in the south to something in the order of that now experienced in southern portions of Illinois, Indiana and Ohio.

These increases in temperature and precipitation may be suggestive of a future lush environment. However, evapotranspiration is also expected to increase considerably, in the order of 170 to 280 mm, more than offsetting the increases in precipitation. As a result, moisture deficiency becomes a critical factor for crop growth.

The importance of moisture supplies is reinforced when year to year variability in precipitation is superimposed on the norms expected in the climate change scenarios. In the absence of information on the degree to which a variability in annual levels of precipitation might change in the climate scenario, it is assumed that growing season precipitation would continue to vary year to year about the norm in a similar manner to the 1951-1981 period.

EFFECTS ON CROP YIELDS

The eight major crops produced on the various types of land found throughout Ontario are grain corn, barley, oats, winter wheat, soybeans, hay, fodder corn and potatoes. To estimate the extent to which yields for these crops would be affected by changes in thermal and moisture conditions, a crop productivity model is employed. Yield responses to changes in long-term climatic norms are estimated by adjusting those input parameters of the model which are sensitive to increased CO_2 in the atmosphere. Effects of precipitation extremes under the current and altered climates are estimated using a similar procedure. A summary of the regional implications of the expected changes in agroclimatic conditions on crop yields follows.

The yield levels for the forages and cereal grains currently grown in the northern reaches of the province would increase substantially given the expected climate changes. Furthermore, the array of crops that could be grown would expand to include grain corn, winter wheat and soybeans. Variations in precipitation from year to year however, would pose a risk to crop production. Generally, the drier years would limit production on lands with a lower tolerance to droughtiness, but these losses would be countered by enhanced prospects on lands with relatively high moisture reserves. The opposite would hold true for years with above average levels of precipitation.

Although the longer and considerably warmer summers would enhance conditions for plant growth in the central regions of the province, increases in moisture stress would tend to negate these benefits. The negative effects would be particularly noticeable on lands with a relatively low drought tolerance. However, the production opportunities for many field crops would be enhanced in years with greater than average levels of precipitation during the crop growing season.

In the southern regions, yield levels for most major crops would be expected to decline on most land types under the climate change scenarios. Temperatures would be expected to exceed the optimal levels for crop growth, and moisture stress stemming from increases in potential evapotranspiration would be even more pronounced. Yields for small grains, oilseeds and potatoes would suffer the most under these conditions. Yields for grain and fodder corn on lands with a low resistance to moisture deficits would be expected to decline, but increases would be feasible on lands with large moisture reserves.

EFFECTS ON LEVEL AND VALUE OF CROP PRODUCTION

The effects of climate change on crop production and value are ascertained assuming present patterns of land use. The analysis involves comparing current levels of production and crop value to changes in average crop yields under each climate scenario. Thus, the study isolates the effects of climate change on current production, rather than forecasting probable adjustments in crop production patterns.

One approach to assessing aggregate impacts of these climate changes on the agricultural economy is to assume no adjustments in land-use patterns. Using this rather simplistic approach, current levels and total value of crop production in the province would decline. The production of potatoes, soybeans and winter wheat appear to be especially vulnerable to the specified changes in climate. Declines in provincial production levels for oats and barley would be expected, and production levels for grain corn would also suffer. The two climate change scenarios would have only marginal effects on provincial levels of hay and fodder corn production with no adjustments, and assuming current economic conditions. Depending on the scenario used, the annual loss in the total value of the eight major crops would be in the order of $101 million to $170 million (7-12 per cent). In wetter years the loss would be reduced, but it would be even greater in drier years.

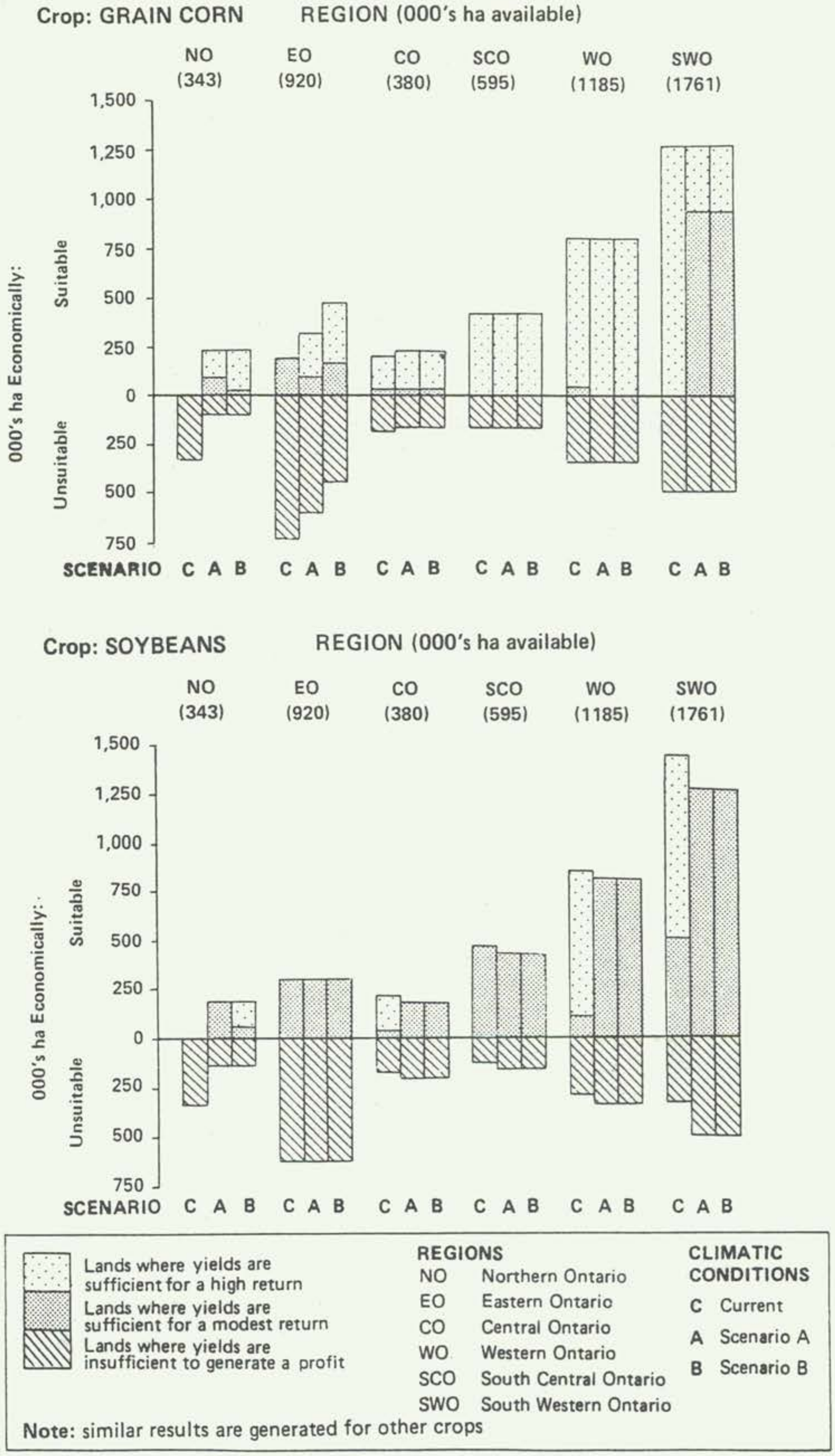
EFFECTS ON THE ECONOMIC SUITABILITY OF LAND RESOURCES FOR CROP PRODUCTION

In an effort to estimate the types of adjustment in agricultural production which might result from climate change, changes in the areas of land suitable for each major crop were examined (see Figure 1 for example). From the provincial perspective, the climate changes would reduce the economic opportunities for the production of grain corn, winter wheat, soybeans and oats; have little impact on the prospects for barley production; and increase the economic potential for fodder corn production.

The overall effect of the specified changes in climate on the economic opportunities for grain corn would be a modest increase in the total area which would be economically suitable for the crop, mainly in the north, but a sharp decline in the area with a high economic potential, notably in the south.

The economic outlook for the production of soybeans and winter wheat in Ontario would suffer under the climate change scenarios, despite the expansion in the area of land in the north which would be economically suitable. Other regions would experience losses in total area suitable for soybeans and wheat, and particularly in area of land which would provide a high return to investment in these crops.

FIGURE 1: EFFECTS OF CLIMATE CHANGE ON ECONOMIC SUITABILITY OF LAND RESOURCES FOR CROP PRODUCTION



Note: similar results are generated for other crops

Losses in economic potential for oats would be confined to the western and southern part of Ontario. The economic suitability of lands for oat production in the other regions, and for barley production in all regions would not be greatly affected by the specified changes in climate.

While the economic prospects for fodder corn would be enhanced considerably in the northern and central regions, these benefits would be offset by reduced opportunities in the south. Overall, Ontario would experience slight increases in the economic opportunities for fodder corn production.

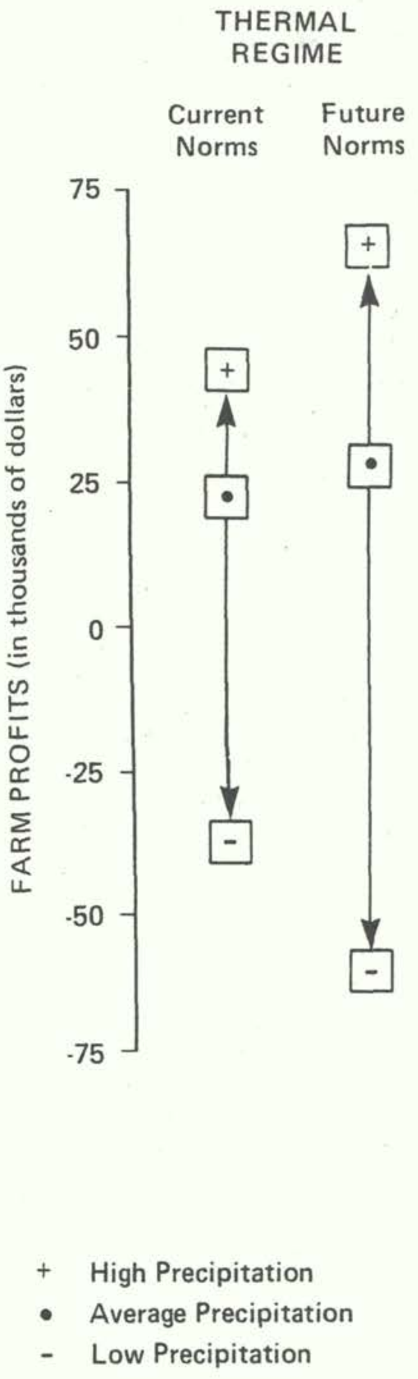
IMPLICATIONS AT THE FARM LEVEL

A cash grain farm model is used to estimate the impacts of climate change on resource allocation and product mix, and hence on farm profits. This analysis recognizes that producers are able to adjust their decisions given a change in climate norms. The analysis is conducted for a 'typical' 200 hectare cash grain farm in the southern part of the province. The model is run for two sets of conditions. The first approximates current climate and economic conditions, whereas the second assumes a climate altered by a doubling in CO_2. Yields for cash grains are adjusted to reflect the altered agroclimatic environments, and all other conditions including production costs and crop prices are maintained at initial levels.

The analysis also addresses the degree to which variability in precipitation implies a risk to crop production and farm profits. This is assessed by assuming decisions regarding the operation of the 'typical' cash grain farm are based upon prevailing economic conditions and long-term climate normals. Then, grain yields are adjusted to those estimated for the extremes of precipitation. This provides a basis for judging the combined effects of climate change and variability on crop production, value of production, and farm profits.

Long-term changes in climate normals could have profound effects upon cash grain farms in southern Ontario (Figure 2). Substantial increases in farm profits would be possible, but this would require a greater reliance upon grain corn production. The vulnerability of monoculture farming systems to market fluctuations and to diseases and pests, as well as the potential adverse impacts of continuous row cropping on land quality, raises several questions regarding the long-term sustainability of such a farm enterprise. Furthermore, fluctuations in annual farm profits attributable to precipitation extremes would tend to increase under the altered climate (Figure 2). This instability could trigger additional problems at the farm level including inadequate cash flow and increases in debt load.

FIGURE 2: IMPACTS OF CLIMATE CHANGE AND VARIABILITY AT THE FARM LEVEL



PRODUCTION OPPORTUNITIES FOR OTHER CROPS

The analysis reported so far has pertained to the eight field crops which are most important in the Ontario agricultural sector. The longer, warmer growing seasons and the milder winters associated with elevated levels of CO_2 would expand the opportunities for producing horticultural crops throughout Ontario. It would be feasible to produce frost-sensitive crops such as sweet corn over a wider range. The production prospects for crops sensitive to extreme winter temperatures would also be improved; the commercial production of apples, for example, would be possible throughout much of the province. The anticipated increases in summer and winter temperatures would be sufficient to allow the production of tender fruits such as grapes in most areas of southern and central Ontario; but the altered climate in eastern and northern Ontario would continue to be unsuitable for these crops.

It would appear that the opportunities for introducing new crops to Ontario under the altered climate regime would be modest. Potential benefits of these climate changes would probably be noticeable in two areas. First, the higher yielding cultivars that are currently used in the longer season of the Central United States would in all likelihood be suitable to Ontario. Second, the warmer temperatures, especially during the winter months, will be much more favourable for fruits and vegetables, and production would not be limited to lakeside locations. It should be feasible to produce a wide range of horticultural crops over large portions of the province under the altered climate regime.

EFFECTS ON ONTARIO'S FOOD PRODUCTION POTENTIAL

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

CONCLUSIONS

This study demonstrates that climate changes could have profound effects on Ontario's agri-food sector. New opportunities for agricultural production in northern areas of Ontario suggest prospects for a major expansion of the agricultural economy there. Similar opportunities could be expected in northen Wisconsin and Michigan and parts of New York State. In other regions, especially the agricultural heartland in southern Ontario, production prospects for many common crops would be diminished. Similar implications are likely for southern Wisconsin and Michigan and parts of the states of

Illinois, Indiana, Ohio, Pennsylvania and New York. It may be possible to compensate for these losses by adopting crops that have a higher tolerance to moisture deficits. In any event, there are significant ramifications for the established infrastructure of agri-food systems in the Great Lakes region, and in Ontario in particular.

The costs of ignoring these changes could be high, both for individual operators and for the province as a whole. However, by adjusting to the changed conditions some interesting prospects emerge. In addition to the potential for boosting the agricultural economies in northern and eastern areas of Ontario, there are enhanced opportunities for diversifying agriculture in other regions of the province. The length of the growing season is likely to become less of a constraint, but moisture deficit is expected to become a more important limiting factor.

The implications for other sectors and for policy are wide ranging. For example, there are obvious implications for crop insurance. Crop breeding might focus on hybrids which are tolerant of moisture deficits. There may be a need for processing and marketing initiatives for new products. Increased use of irrigation may occur, with more demands on water supplies at a time when other sectors are also drawing upon a diminished water supply.

These conclusions are extremely speculative. Very little research has been conducted into ecological and socio-economic impacts of climate change, and considerable uncertainty exists. There is little agreement on the time frame for many of the possible changes, and other conditions which also influence agriculture and other sectors of the economy are changing as well. Nonetheless, the potential impacts of climate changes associated with the 'Greenhouse Effect' are of sufficient magnitude that sensitive areas should be identified and policy implications considered.

ACKNOWLEDGMENTS

The research referred to in this paper was undertaken under the aegis of the Canadian Climate Program by the Land Evaluation Group (LEG) at the University of Guelph. The research team comprised Barry Smit (Project Director), Michael Brklacich (Project Manager), Deborah Bond, Murray Brown, Ronald Lohr, Ray McBride, Murray Miller, Truman Phillips and Stephen Rodd. The research drew upon the cumulative expertise of scientists affiliated with the LEG, Agriculture Canada, and the Atmospheric Environment Service. The research team gratefully acknowledges the contributions and support of the Research Branch and the Regional Development Branch of Agriculture Canada, the Atmospheric Environment Service of Environment Canada, the Ontario Ministry of Agriculture and Food, and the Social Sciences and Humanities Research Council of Canada.

LIKELY EFFECTS OF CLIMATE CHANGES ON WATER LEVELS IN THE GREAT LAKES

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INTRODUCTION

The Great Lakes system, Figure 1, is one of the world's major water resources. It contains approximately 23,000 km^3 of water, representing 95 percent of the United States's and 20 percent of the world's fresh surface water. It is also one of the most intensively used fresh water systems in the world, serving multiple interests including navigation, hydropower, recreation, and riparian. Some significant uses of the Great Lakes have become dependent upon the small variation in water levels, resulting in system sensitivity to even small changes in the lake levels. Climatic change, represented by global warming or cooling, could have a significant effect on the Great Lakes and the surrounding region. Because of their large surface areas and constricted connecting channels the Great Lakes filter out much short-term variability and react primarily to longer period fluctuations represented by climatic change.

Examples of the regional response to global change are demonstrated by the northern hemisphere warming and cooling trends during this century. The warming over the northern hemisphere between the 1920's and the 1960's is well documented in the records of the Great Lakes. The current northern hemisphere cooling trend is also reflected in the Great Lakes region. The annual mean of the air temperatures around the Great Lakes for the period 1960-1980 is 0.8°C cooler than the prior 30 year period. The precipitation over the past 20 years has been extremely high with very little variability. For the upper Great Lakes 17 out of the past 21 years have had above average precipitation. The cooling trend has combined with the high precipitation regime to give exceptionally high water supplies to the basin. The past several years have brought record high lake levels, flooding in low lying areas and extreme erosion damages along the lakeshore bluffs.

A current concern is that a climatic warming, resulting from the increase of CO_2 and other greenhouse gases, could result in major changes to the hydrologic cycle and ecosystem of the Great Lakes. Estimates indicate a temperature rise of about 4°C might be expected over the latitudinal range of the basin, 40°-50° north, due to a doubling of CO_2 concentrations in the atmosphere over the next 100 years (NRC, 1983; Cohen, 1986). In addition, changes in the amount and seasonal distribution of precipitation would likely occur. The basin has not been widely effected by drought and low water supplies in the past. This could likely change as a result of future global warming. This study addresses, in a preliminary fashion, the potential impacts of climate warming on the water supplies of the Great Lakes.

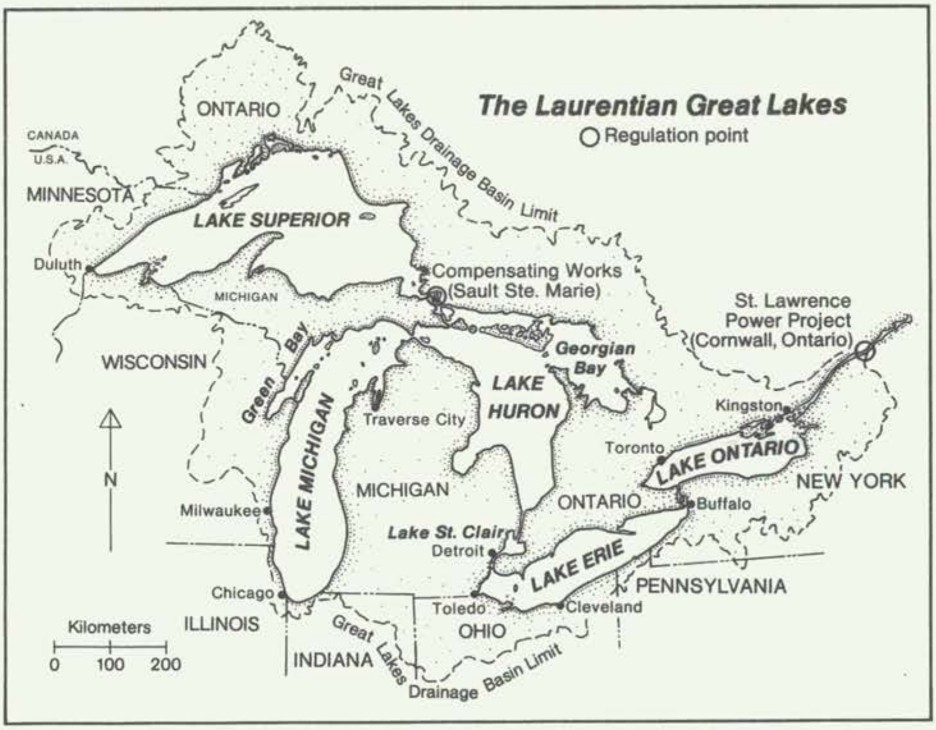

Figure 1. The Great Lakes System

FUTURE WATER SUPPLIES AND LAKE LEVELS

The Great Lakes have historically enjoyed a relatively small range in lake levels, approximately 152 cm from the average annual maximum to the average annual minimum. Superimposed upon the average levels are seasonal cycles of 30-40 cm. In addition, storm surge and wind set-up can raise the water levels by as much as 250 cm. Lake Erie is particularly notable for wind setup. During severe storms there can be as much as an 500 cm difference between the eastern and western ends of the lake. Because of their large surface areas the spatial average levels of the lakes respond primarily to longer term changes in the water supplies. The probable impacts of climatic warming will be to decrease the water supplies by increasing the evapotranspiration from the land surface thus resulting in smaller runoff into the lakes, increasing the evaporation from the lake surfaces and finally by any changes in precipitation patterns which may occur.

While accurate assessments of the impact of a doubling of CO_2 on Great Lakes hydrologic parameters await refinement of the Global Circulation models, preliminary estimates of the impact of climate warming on the Great Lakes net basin supplies have been undertaken. The net basin supply (NBS) is defined as the sum of the precipitation on a lake and the runoff into the lake from its basin minus the evaporation from the lake surface. Quinn and Croley (1983) estimated that a 3°C temperature rise coupled with a 6.5 percent increase in precipitation would decrease the net basin supply to Lake Superior by 10 percent. A similar 3°C temperature rise with no precipitation increase would decrease the Lake Erie net basin supply by 33 percent. Cohen (1986) indicated decreases in net basin supply for a 4°C warming of between 4 and 21 percent depending upon the assumptions used. The computations are very sensitive to changes in precipitation, wind speed and humidity. Possible increases in consumptive use due to the climatic warming would further decrease the water supplies to the system.

Considering the wide range of preliminary estimates, two scenarios were chosen to represent possible outcomes. The first assumes a 15 percent decrease in net basin supply for each of the lakes while the second, a more severe case, assumes a 30 percent decrease. Note, for comparison, that the low supply regime of the early 1960's reduced the NBS by 20 percent, 30 percent and 40 percent for Lakes Superior, Michigan-Huron, and Lake Erie, respectively.

Historically the Great Lakes have varied considerable over the 1860-present period of record, Figure 2. The hydrologic data selected to test the scenarios are for the period 1962-1980 (Quinn and Kelley, 1983). This is a representative period which includes the extreme low water levels of the mid-1960's as well as the extreme highs of the early 1970's. Thus it will provide the impacts of climate change at both extremes. The computed net basin supplies for each year were reduced by 15 percent and 30 percent, respectively to represent the climate change scenarios. Under a doubling of CO_2 ice cover on the Great Lakes would be greatly reduced, (Assel, 1987). Thus it was assumed that ice jams, and the resulting ice retardation, in the connecting channels would be negligible.

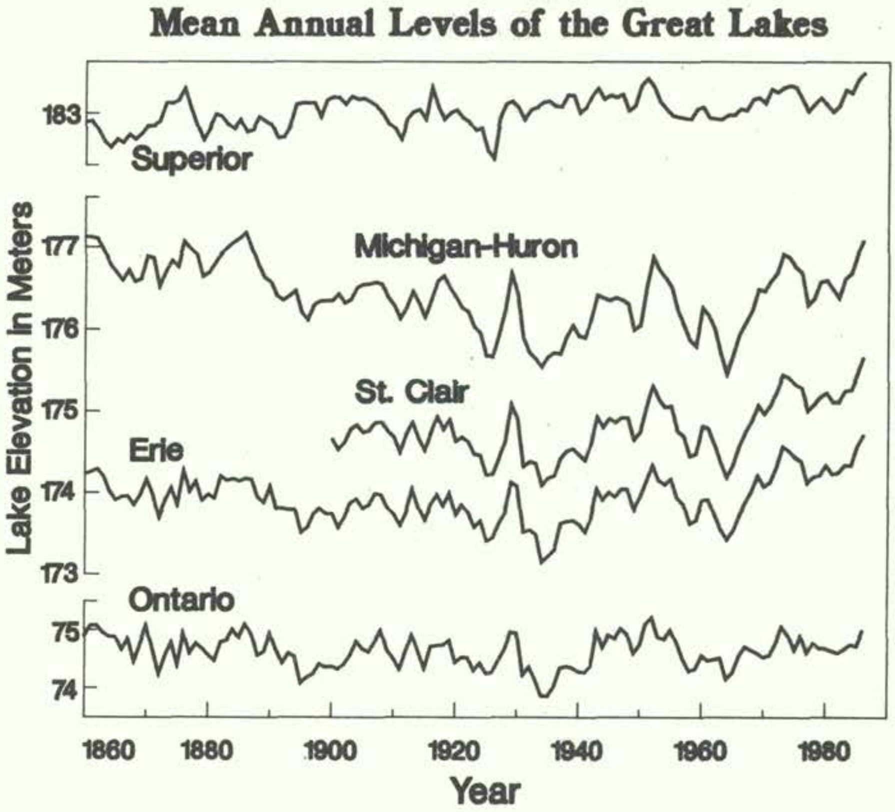

Figure 2. Great Lakes mean annual water levels

The scenarios were run by using the Great Lakes hydrologic response model (Quinn, 1978). The model, shown in schematic form in Figure 3, is a routing model which takes as inputs the monthly hydrologic data and computes the resulting sequence of lake levels and flows in the connecting channels. This analysis assumes that the outflows of Lake Superior will be reduced by the reductions in net basin supply and Lake Superior water levels are not computed. Lake Superior is regulated but the existing regulation plan, Plan 1977, was developed to redistribute impacts of the high water supply regime of the 1970's and 1980's. The regulation plan is not designed to operate under the prolonged low net basin supplies indicated by the scenarios and is probably not representative of the regulation plan that would be in effect at the time. Lake Superior level changes would be a function of the existing regulation plan. Likewise, effects on the water levels of Lake Ontario are not computed as they would also be dependant upon the regulation plan in effect at the time. The starting elevations were determined by an iterative process and represent the elevations which would have occurred under the climatic warming.

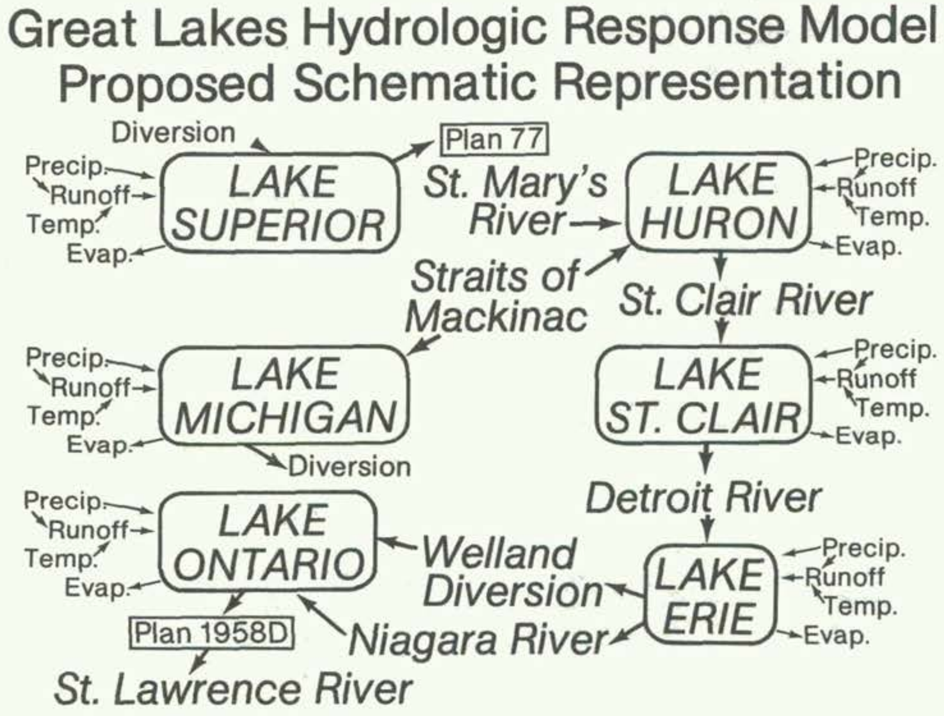

Figure 3. Hydrologic response model schematic

The results are given in Table 1. Both scenarios result in a major decrease in Lake levels. In addition, the annual range in lake levels would be reduced. On Lake Michigan-Huron, for example, the range would be reduced from 146 cm to 140 and 130 cm respectively for scenarios 1 and 2. While these lowerings would be beneficial during times of extremely high lake levels, they would be disastrous during periods of low supply and lake levels. This decrease in range is primarily due to a larger decrease under high NBS which reduces the higher lake levels more than the lower levels. The range in levels for Lakes St. Clair and Erie are also reduced but by lesser amounts. The seasonal cycle would also be modified due to major changes in snowfall and spring snowmelt runoff, coupled with enhanced lake evaporation.

Table 1. Equilibrium effects on lake levels

	Lake Level Lowering in cm	
Lake	Scenario 1*	Scenario 2**
Michigan-Huron	77	156
St. Clair	60	125
Erie	51	106

* 15 percent decrease in NBS

** 30 percent decrease in NBS

POTENTIAL IMPACTS

The lowering of the lake levels would adversely impact many Great Lakes uses including navigation, hydropower, recreational boating and perhaps water quality. The Great Lakes/ St. Lawrence Seaway is a major freshwater transportation system. This system depends upon adequate depths in the connecting channels and harbors to function at full capacity. Under the climate warming scenarios, decreased channel depths would necessitate extensive dredging in both the connecting channels and the major harbors. Much of this area has not been dredged in the past 20 years. In a number of areas the dredged material is highly contaminated, creating a problem with spoil disposal. On the other hand a decreased ice season could lead to an extension of the current navigation season, contributing to better vessel utilization and a decrease in stockpiling.

The waters of the Great Lakes are extensively used for hydropower production. Facilities range from low head plants in the St. Marys River to high head facilities in the Niagara and St. Lawrence Rivers. A climatic warming would result in decreased flows and water surface elevations which would contribute to lower hydropower production. This could be important, as hydropower is cheap and nonpolluting when compared to its primary alternative, fossil fuel. Fossil fueled and nuclear power plants sited around the lakes use lake water for cooling. A climatic warming could produced increased consumptive use of water which would further exacerbate the anticipated low lake levels.

The Great Lakes system is one of the prime recreational boating areas in the country. The three county area around Detroit has more boating registrations than any other area in the U.S. The lower lake and connecting channel water levels resulting from climatic change would greatly reduce the areas currently accessible to small craft, including the small passenger vessels that are operating in many areas at the present time. This could require extensive private dredging and the rebuilding of ramps.

POTENTIAL POLICY ISSUES

The Great Lakes are a shared resource between the United States and Canada. There are also numerous state, provincial, county and municipal jurisdictions leading to a complex jurisdictional structure. This will require a coordinated approach to policy development for coping with lowered lake levels. The policy implications of long term lowered lake levels are far different than the major policy deliberations during the past several years which have emphasized coping with high lake levels. A major thrust will be on how to keep water in the system rather than how to get rid of it. This will require extensive revision of the existing regulation plans as well as the possible regulation of Lake Michigan-Huron and Lake Erie. Major policy decisions will have to be incorporated into the regulation plans including the distribution of benefits between commercial, riparian, recreational and ecological interests, between upstream and downstream interests, and finally between the many jurisdictional interests.

The debate over interbasin diversion of water is also likely to intensify. There will be demands to increase the amount of water diverted into the Great Lakes through the existing diversions into Lake Superior as well as the consideration of new diversions. At the same time efforts will likely be underway to curtail the water diverted out of Lake Michigan at Chicago. This will be opposite to the current thrust to increase the diversion at Chicago and limit the diversions into Lake Superior.

Unfortunately there is no historical analog to provide insight as to what the societal response will be to a prolonged period of low lake levels. The low water levels in the mid-1960's did not last long enough to be a valuable analog. However during this period there was increased emphasis on bringing additional water into the system, on improved regulation, and on compensating for anthropogenic lake level lowering.

CONCLUSIONS

Global warming will have severe implications for the Great Lakes Basin. A 4°C warming is extreme when compared with the warm and cool regimes experienced during this century. The difference between the warm regime of 1930-1960 and the cool regime of 1960-1980 was only about 0.8°C. Assuming that the CO_2-induced warming is approximately proportional to the increase of the logarithm of the CO_2 concentration in the atmosphere (NRC, 1983), the temperature could rise by 1°C by 1995 and 2°C by about 2020. Thus, impacts of climatic change may be realized relatively quickly. The resulting lower lake levels will require a new paradigm of how the lakes will be viewed from social, economic, and ecological perspectives. New policies will have to be developed and implemented to balance the competing interests. It is therefore important that present policy analysis consider a wide range in fluctuating water levels in addition to the high lake level conditions on the past two decades. This analysis provides a preliminary assessment of the likely impacts. More extensive analyses are currently underway. However, greatly improved accuracy will await refinements to the global climate models used to develop the scenarios. Thanks to the current climatic regime, the Great Lakes now have an abundance of fresh water. Global warming indicates that this may not always be the case.

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CLIMATIC CHANGES - IMPACTS ON GREAT LAKES LEVELS AND NAVIGATION

BY

JOSEPH RAOUL, P.E.[1], AND ZANE M. GOODWIN, P.E.[2]

PRESENTED AT

FIRST NORTH AMERICAN CONFERENCE

ON

PREPARING FOR GLOBAL CLIMATE CHANGE - A COOPERATIVE APPROACH

The subject of this Conference "Preparing for Global Climate Change" is very compelling, and the caveat "A Cooperative Approach," totally pertinent. It takes the cooperation, or the union of a whole array of disciplines from climatology, meteorology, hydrology, hydraulics, geography, the environmental sciences, sociology and of course, economics to tackle the issue; moreover, it takes the participation of several agencies from both sides of the international Great Lakes border to invest the necessary resources to arrive at a solution or a plan of action to face the eventuality.

My topic at this Conference is the impact of climatic changes on the Great Lakes levels and the effects of these changes on navigation. While we cannot predict with certainty the shape of the future climate, and are still awaiting salient answers, we must realize that the decision maker very seldom has the advantage of precise foresight. He has to develop policies, establish plans of action and make the most of the future with all its unknowns and uncertainties using the past as sounding board.

Speaking of the past, what do we know or how comfortable are we to make inferences?

There is no strong evidence, at this point, to suggest any drastic change in the levels of the Great Lakes. Over the period-of-record which extends back to 1860, the levels have varied within a range of 4.17 feet for Lake Superior, 6.59 feet for Lakes Michigan-Huron, 6.84 feet for Lake St. Clair, 6.26 feet for Lake Erie and 6.61 feet for Lake Ontario (see Table 1). The range of variation for Lake Superior is smaller, only because of its upstream location (no major inflow rivers), its large size and storage capacity, and to some degree, because of it being regulated. Within these ranges, the levels have followed a seasonal variation reaching their "high" usually during the summer months and their "low" during the winter months.

The cycles of seasonal increases and decreases in water levels on the lakes do not take place at the same time nor with the same magnitude of rise and fall. As far as trends toward permanently higher or lower levels, observation of the Great Lakes hydrographs for the period of record does not reveal any discernable pattern. We observe, for example, that Lakes Michigan-Huron remain below average for some years then revert to their trend years later, remain above average for some more years and so on and so forth; such a behavior which is common to all the Great Lakes is attributable more to the so called persistence

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Table 1

Extremes on the Great Lakes and Date of Their Occurrence

	Minimum	Maximum	Chart Datum	Range
Lake Superior	April 1926	November 1985		
	598.23	602.42	600.00	4.19
Lake Michigan-Huron	March 1964	October 1986		
	575.35	581.94	576.8	6.59
Lake Erie	February 1936	June 1986		
	567.49	573.75	568.6	6.26
Lake Ontario	November 1934	June 1952		
	241.45	248.06	242.8	6.61
Lake St. Clair	January 1938	October 1986		
	569.86	576.70	571.7	6.84

in hydrology than to any other reason. Hence, this makes it difficult, and more precisely, very uncomfortable for the satistician to make any inference as to trends towards a permanent rise or fall in the levels of the lakes.

In terms of persistence, the information shown on Figure 1 is pertinent. It shows the cumulative departures from the mean levels and runoff for three lakes and two rivers in generally the same climatological areas. A trend downward from 1900 until the 1940's followed by an upward trend from 1940 to date, does support the idea that lows tend to follow lows and vice versa, as previously shown for the Great Lakes. From these observations which are based on a relatively short period (120 years) of record, it makes more sense to think in terms of climate variability than climate change, the latter implying a permanent rise or fall in the levels of the Great Lakes.

Do the changes in the climate really affect the trend in variation of the Great Lakes Levels?

It is hard to tell, based on the previous considerations. Inference based on several thousand years of record might be more conclusive. In a briefing conducted by the International Joint Commission in 1985, Dr. Frank Quinn of NOAA noted that preliminary studies by the United States Geological Survey show variations in the levels of Lake Michigan much larger than those experienced over the past 120 years. The works done by Dr. Curtis Larsen, using evidence of ancient beaches dated more than 5,000 years back, suggest that the lake levels in the future could be more dramatic than normally expected. Such perspective however may be modulated by the fact that the conditions 5,000 years ago were very different from today, because of isostatic rebound and uplift during the intervening time. Research is warranted to generate information using either tree ring methods, more sophisticated regression models, geologic or archeologic models and the capabilities of the electronic computers.

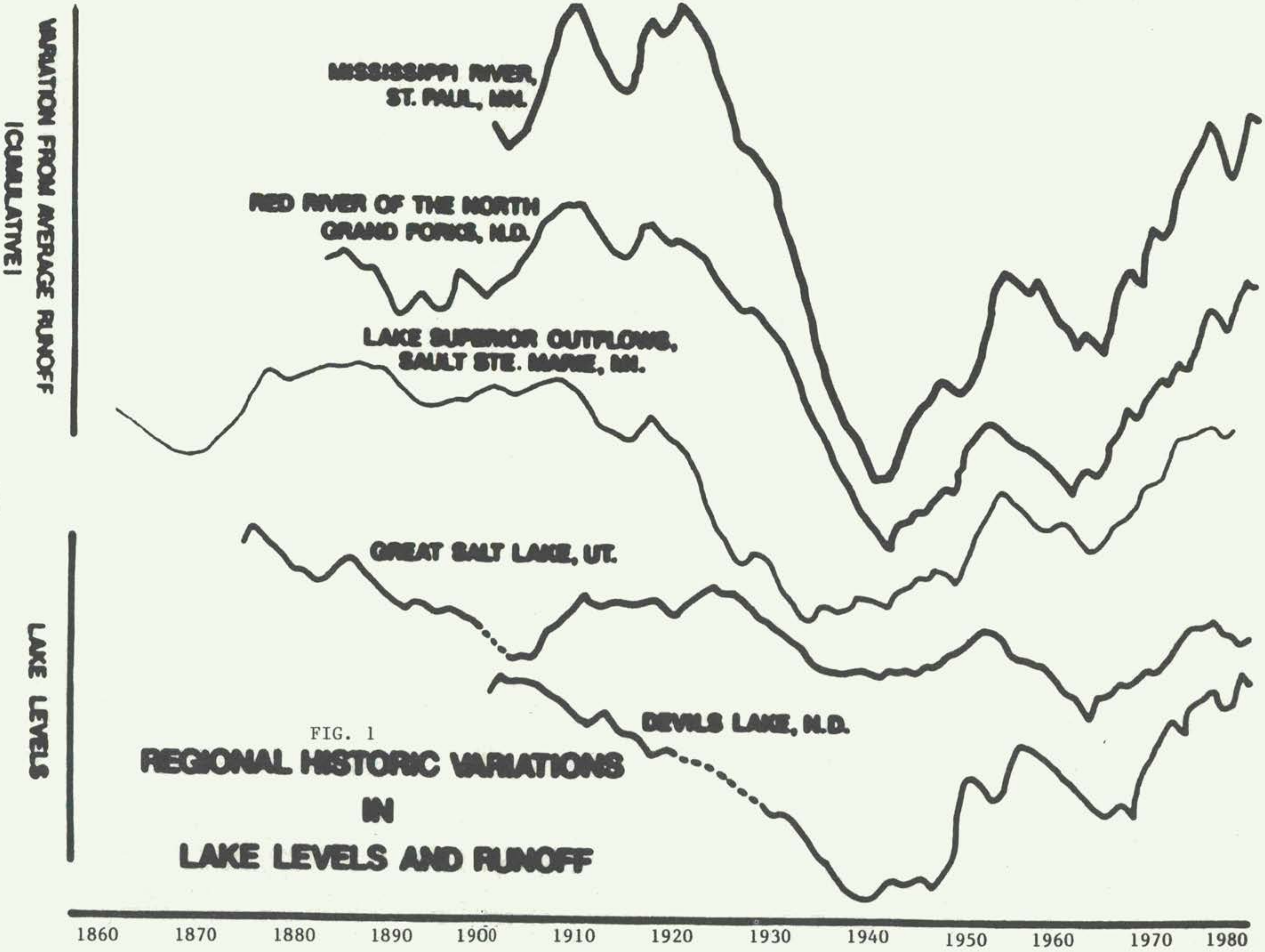

FIG. 1
REGIONAL HISTORIC VARIATIONS IN LAKE LEVELS AND RUNOFF

A Look at the Hydrology of the Great Lakes

The many uses of the Great Lakes fall under four major categories: power, navigation, recreation and shore property interests. These uses depend basically on the magnitude of the levels of the lakes and the flows in the channels and connecting rivers. By their very nature, these four categories of use tend to compete with each other: power generation is favored by dependable consistent outflows; higher levels are beneficial to navigation; while riparian owners and recreation users welcome neither too high levels, which may affect their properties and destroy their beaches nor too low levels which may interfere with much of the recreational use of the lakes. Environmental resources such as wetland habitats can also be significantly affected by fluctuating lake levels. Such diversity has been the focal point in the modern concept of Great Lakes regulation which would be ideal if a truly optimum regime of level and outflows could be obtainable all the time.

The efforts of man to manipulate the levels of the lakes go back to the early part of this century with the completion of the control works at the outlet of Lake Superior on the St. Marys River at Sault Ste. Marie, in 1921. Almost half a century later, in 1960, the regulation of Lake Ontario began with the operation of the St. Lawrence Seaway and Power Project.

The myriad of different plans for regulation that have been developed over the years and the continuing effort to refine regulation plans today attest to the complications involved in trying to improve a system that is already naturally regulated with an immense storage capacity combined with highly restricted outflow capacities. Another significant feature of this system is its water surface area which is so vast that small changes in the levels of the lakes account for enormous quantities of water.

With such a peculiar physiography, how do we account for the change in lake level resulting from climatic changes and how do we integrate such changes (positive or negative) into the regulation of the lakes? In conventional or traditional Great Lakes hydrology parlance, two categories of factors affecting the levels of the lakes have been defined and taken into account so far, namely the natural and artificial factors. The natural factors like precipitation, runoff, evaporation, ice conditions, transitory changes due to wind action and barometric pressure differences induce the natural variation in the lake levels. The lake levels will vary depending on the balance between the volume of water received by the lake, the so-called supplies, and the volume of water removed from it. These two parameters are changing continuously due to natural hydrologic and meteorologic deviations. The artificial factors are those induced by man either through diversion of water into, out of, or between the lakes, or through modification in outflows from natural outlets by channel modification and regulatory works... the physical instruments for regulation... an expression of my own. Regulation could be redefined as an effort by men to harmonize the effects of the natural factors with the use of the artificial factors. Regulation could be a fairly accurate exercise if we did not have to deal with the probabilistic nature of the natural factors....the continuous saga of the hydrologist. Such a level of difficulty is compounded with the introduction of the idea of change in climate... change in cloudiness...change in precipitation... change in temperature... change in evaporation... and consequently change in lake levels and so on and so forth.... Such a scenario suggests, of course, the introduction of a third category of factors affecting the lake levels, and until more formal resolution we will call it The naturally induced artificial factors. They reflect of course, the consequences of man-made intervention (greenhouse effect and other environmental alterations) in the overall climatic variation and their probable impact on Great Lakes levels.

It is premature to suggest integration of these changes in plans for regulation, as such changes are yet to be defined, categorized and/or measured with some accuracy. At this point in the development of the hydrologic thought it is not certain which way the levels will be affected; many suggestions have been advanced so far, not necessarily in chorus (or in agreement with each other). Some scientists suggest that the extreme low lake levels of the past are likely to be the mean lake levels of the future. Another school of thought suggests that the record high levels that were experienced in 1985 and 1986 are low compared with levels to be experienced within the next fifty or one hundred years. Another group of researchers argue that the climate system will at some time be pushed beyond some threshold and will leap into a new mode of operations, the consequence being a sudden drop or rise in the level of the Great Lakes. Such an array of projections could be discouraging if we were not aware of the complexities of the solar system.

Navigation and the Great Lakes

Changes in the levels of the Great Lakes are prone to serious repercussions on the economy and well-being of the nation. Navigation on the Great Lakes is one of the key factors in the economy of the region and its success is directly related to the lake levels. It must be analyzed as one key parameter in the development of contingency plans for climate changes.

The system with its connecting channels and the St. Lawrence River (Fig. 2) represent a 2,350 mile waterway from the heart of the North American continent to the Atlantic Ocean. Fig. 3 shows a profile of the Great Lakes-St. Lawrence Seaway navigation system while Table 2 shows the physical dimensions of the system.

The system provides a transportation base which is vital to the Region's economic growth. In the United States the system borders on and directly affects eight different states. Within the Great Lakes Basin itself lives one seventh of the population of the United States. The United States portion of the basin produces about one sixth of the national income and accounts for over one fifth of the manufacturing employees and capital expenditures. One third of Canada's population lives in the Ontario portion of the basin, where one third of national income and over half of its manufacturing employment and capital expenditure is found. Since inception of navigation on the Great Lakes in 1678, the system has grown to accommodate 225 million tons of United States waterborne commerce as recently as 1979 and 148 million tons in 1985. Some statistics are shown in Table 3, for the four basic commodities; iron ore, coal, limestone and grain.

The abundance of iron ore and limestone near the upper Great Lakes, and coal within 200 miles of the southern lake ports, represents an incomparable combination of resources which along with the growing consuming areas has necessitated the location of 40 percent of the nation's steel making capacity along southern Lake Michigan and the western and southern Lake Erie shores. An

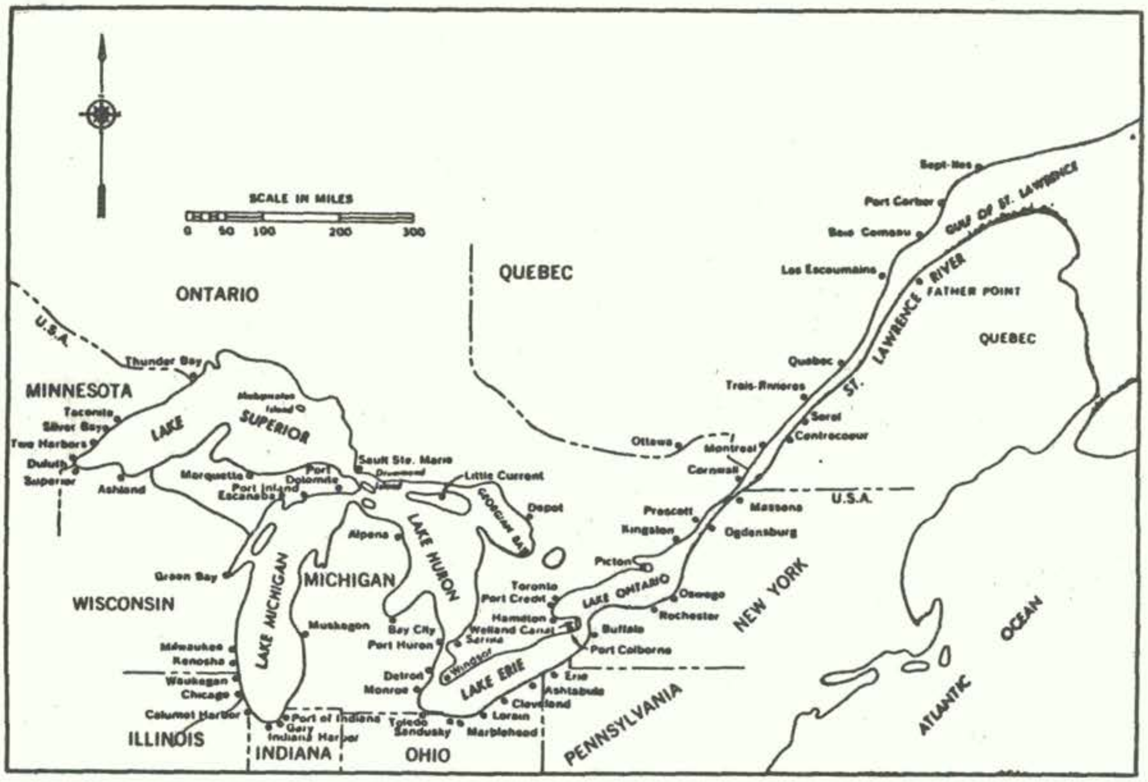

Figure 2
GREAT LAKES—ST. LAWRENCE NAVIGATION SYSTEM

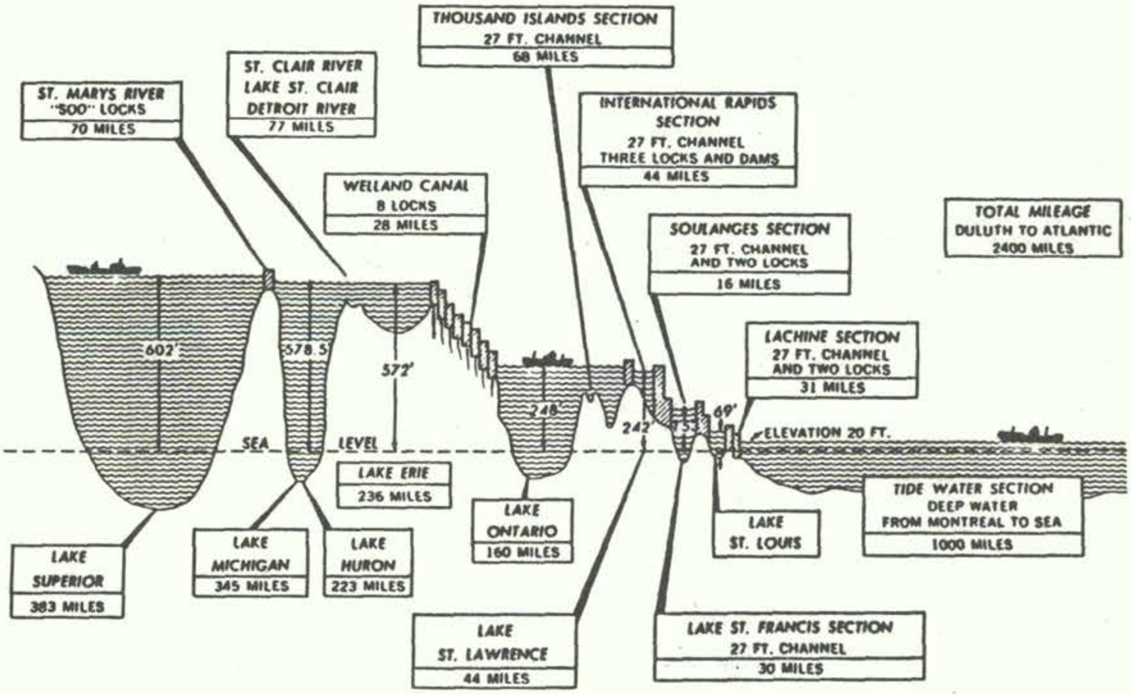

Figure 3
PROFILE OF GREAT LAKES—ST. LAWRENCE NAVIGATION SYSTEM

Table 2
Physical Dimensions of the Great Lakes-St. Lawrence Seaway

	Lakes and Channel			Locks				
Reach	Open Waters (miles)	Channels & Canals (miles)	Depth (min.) (ft.)	Number	Year Completed	Size(ft.) Length x Width	Depth Over Sill (ft.)	Lift (ft.)
Atlantic Ocean to Father Point, Que.	700	---	---	---	---	---	---	---
Father Point to Montreal	300	---	35	---	---	---	---	---
Montreal to Lake Ontario (includes St. Lawrence Seaway)	189	91	27	5 (Can.) 2 (U.S.)	1958 1958	800 x 80 800 x 80	30 30	226 226
Lake Ontario to Welland Canal	160	---	---	---	---	---	---	---
Welland Canal	---	27	27	8	1932	800 x 80	30	326
Welland Canal to Detroit River	236	---	27	---	---	---	---	---
Detroit River, Lake St. Clair, and St. Clair River	---	77	27	---	---	---	---	---
Lake Huron, St. Clair River to St. Marys River	223	---	---	---	---	---	---	---
St. Marys River (includes Soo Locks)	70	2	27	2 (U.S.) 1 (U.S.) 1 (U.S.) 1 (Can.)	1919 1943 1968 1895	1350 x 80 800 x 80 1200 x110 900 x 59	23.1 31.0 35.0 16.8	22 22 22 22
Lake Superior, St. Marys River to Duluth	383	---	---	---	---	---	---	---

Table 3
Great Lakes Bulk Tonnage
(net tons)

	1975	1980	1985
Iron Ore	89,562,198	81,723,442	58,431,773
Coal	39,180,031	41,306,125	36,334,525
Grain	24,511,214	31,868,631	20,055,902
Limestone	37,681,469	28,011,597	24,992,777
	190,934,912	182,909,795	139,814,977

Source: Annual Reports of the Lake Carriers' Association additional 33 percent of steel making capacity not in the basin is served by Lake Erie ports. Other sectors of the regional economy, including agriculture and electric utilities are also dependent on Great Lakes shipping. It is obvious that the importance of navigation on the Great Lakes in the economy of the two nations is paramount.

Lake Levels and Navigation

It is generally safe to assume that above a given draft, modestly higher levels on the Great Lakes rivers and connecting channels are more beneficial to navigation than lower levels. It is also true that within a certain limited range, the benefit to navigation as related to lake levels is almost a quasi-linear relationship. Given certain constraints however (width and length of lock chambers, vessel size, location, type of transportation, etc.) the occurrence and availability of depths above a certain elevation or at some locations may not necessarily be of tangible consequences. Within the same theoretical range however, a decrease in level may or will always be detrimental. Consequently, the impact of climate changes on the levels of the Great Lakes could be construed as inconsequential to navigation if the changes are positive up to a point, and of serious impact if they are negative. In other words they are damaging if they cause a decrease in the levels of the lakes.

A more detailed review of the components of Great Lakes traffic needs to be done to put things into proper perspective. Commercial traffic in the Great Lakes - St. Lawrence River system has three distinct components: the segment within the upper lakes above the Welland Canal, the segment using the Welland Canal and/or the St. Lawrence River and the segment below Montreal.

The iron ore, coal, limestone and grain commodities occupy 85 percent of the Great Lakes traffic while the remaining 15 percent includes overseas general cargo, petroleum products, cement, chemicals, etc. Although overseas cargo is of high value, the vessels must transit the 27 foot Seaway and, therefore, cannot take advantage of depths significantly greater than 27 feet available in other harbors and channels when the lake levels are above low water datum (LWD). Furthermore, losses because of lower lake levels occur infrequently because of rare occurrence of levels below LWD and because the vessels have the option to top off on Lake Erie, which seldom is below LWD. In addition, many of these vessels stop at several ports and do not travel fully loaded, and, therefore, cannot normally take full advantage of water depths available. Consequently, overseas general cargo traffic has not been significantly affected by changes in lake levels, unless those changes would be drastic, in the order of one foot or more, one way or the other. The other commodities mentioned above that make up the 15 percent are generally carried by smaller vessels which cannot take advantage of higher lake levels. Petroleum products, for example, move in small tankers to a large number of receiving ports, with a tanker generally making several stops on each trip. Newsprint is carried entirely in small ships which are not affected by water levels in the ports to which they trade. Commerce in rock salt on the Great Lakes is moved mainly in relatively small vessels which are not really affected by water level fluctuations. It is therefore not an exaggeration to exclude from consideration this portion (15%) of the Great Lakes commerce, as it relates to the impact, positive or negative, of climatic changes on Great Lakes navigation; unless the changes are extreme.

The Issue - Climatic Changes - Their Impact on the Great Lakes Levels and Consequently on Navigation

Based on the previous analysis, the importance of changes in lake levels as they will affect navigation revolves around the 85 percent of cargoes involving the four main commodities previously mentioned i.e., iron ore, limestone, coal and grain.

In terms of contingency the four scenarios that come to mind are as follows:

Scenario 1. The climate is indeed changing, but its impact on the Great Lakes levels will be so gradual as to be imperceptible. Such occurrence may be construed as "status quo" in that we, under the aegis of the International Joint Commission will continue to monitor and regulate the lakes by manipulating the supplies as they occur, using the past information or the period of record as it gets updated. The issue of navigation is therefore moot,

Scenario 2. If, as we mentioned before, the Geologists happened to be correct, the climate at some point in time will be pushed beyond some threshold and leaps into a new mode of operation. The Great Lakes then may experience a sudden drop or rise in level. The level of uncertainty is so high and the magnitude and time of occurrence so undefinable, within the state of the art, that such an event can be construed as a potential "accident". Navigation like any other interest on the Great Lakes may or may not be in jeopardy. Our foresight under such a scenario is weak and inefficient.

Scenario 3. In a third synopsis, we will assume that the climate will change and trigger eventually a rise of, say, one foot in the level of the Great Lakes. Extreme high levels in constricted channels may be inconvenient as they cause restrictions in vessel speed to minimize wake and wash action against the shoreline. The speed reduction however is counterbalanced by the ability to carry a greater load because of the higher levels. Such a situation, which must be of great concern to the riparian owners and shore property interests, will not have a negative impact on navigation. Although some adjustments may have to be made, particularly in the rivers and connecting channels, the resulting impact if any, upstream of the St. Lawrence Seaway would be positive. In terms of preparation or policy for such an eventuality, it is safe to say that there is no urgency.

Scenario 4. Our emphasis and the ensuing considerations will be on the fourth and last scenario based on the assumption that the climate will change and trigger an eventual decrease of one foot or so in the level of the Great Lakes.

At this point, it is important to note that the assumptions of a permanent raise of lowering of the lakes by one foot is not unlikely, based on theoretical studies performed so far at the University of Arizona. These studies, conducted by Dr. Charles W. Stockton have evaluated four theoretical conditions:

a. An increase in mean annual temperature of up to 2°C, with an associated decrease in mean annual precipitation of 10 percent - Warmer and drier.

b. A decrease in mean annual temperature of up to 2°C, with an associated increase in annual precipitation of 10 percent - Cooler and wetter.

c. An increase in mean annual temperature of 2°C, with an associated increase in total annual precipitation of 10 percent - Warmer and wetter.

d. A decrease in mean annual temperature of 2°C, with an associated decrease in total annual precipitation of 10 percent - Cooler and drier.

The preliminary conclusion is that only conditions 1 (warmer and drier) and 2 (cooler and wetter) would be of consequence to the Great Lakes. This is true because for conditions 3 and 4, the net increase or decrease in temperature would likely change evapotranspiration rates and offset the gain or loss from change in precipitation.

Under condition 1 (warmer and drier) the present annual runoff would be reduced by 33 percent resulting in mean annual runoff of 50.4 bgd; under condition 2 (coller and wetter), the mean annual runoff is postulated to increase by 37 percent producing a mean annual runoff of 103 bgd. Under condition 1, the lake levels would decrease, while they would increase under condition 2. In either case the change could be as much as two feet.

The following considerations are based on the assumption that, for some yet unknown reason, the lake would decrease by up to two feet. Navigation will be seriously affected and the over all impact is itemized below:

1. DIFFICULTY TO ACCOMMODATE LARGER VESSELS
2. DECREASE LOAD ON DEEP DRAFT VESSELS (LOSS OF CARRYING CAPACITY)
3. INCREASE IN NUMBER OF TRIPS
4. INCREASE IN TRANSPORTATION COST
5. INCREASE POTENTIAL FOR VESSEL DAMAGE
6. INCREASE OPERATION AND MAINTENANCE COST
7. POTENTIAL SHIFT IN TRANSPORTATION MODE
8. NECESSITY TO DREDGE HARBORS
9. NECESSITY TO DREDGE CONNECTING CHANNELS
10. FURTHER LOWERING OF LEVELS (WITHOUT COMPENSATION)
11. REFORMULATION OF REGULATION PLANS
12. INCREASE IN COST OF COMMODITIES

While these impacts are yet to be quantified, we have developed in the following tables, information relative to five different sizes of Great Lakes vessels and the corresponding loss in carrying capacity resulting from four sequences of lowered levels, i.e., 3", 6", 9" and one foot.

Loss of Carrying Capacity
Due to 3" Lowering

Size of Vessel (Tons)	Capacity Loss (Tons)
60,000	630
45,000	540
28,000	372
27,000	363
21,000	291

Lose of Carrying Capacity
Due to 6" Lowering

Size of Vessel (Tons)	Capacity Loss (Tons
60,000	1,260
45,000	1,080
28,000	744
27,000	726
21,000	582

Loss of Carrying Capacity
Due to 9" Lowering

Size of Vessel (Tons)	Capacity Loss (Tons)
60,000	1,890
45,000	1,620
28,000	1,116
27,000	1,089
21,000	873

Loss of Carrying Capacity
Due to One Foot Lowering

Size of Vessel (Tons)	Capacity Loss (Tons)
60,000	2,520
45,000	2,160
28,000	1,488
27,000	1,452
21,000	1,164

In terms of dollar values, the estimates are highly controversial because of the multitude of factors involved in the cost of transportation and the variety of commodities. In a study performed in 1985, based on July 1979 costs and January 1981 vessel delivery, it was estimated that an increase by one foot of Lake Superior navigating depth from 27 ft. to 28 ft. is worth 50 to 60 million dollars. Such information is yet to be updated, but the order of magnitude is of pertinence.

On the positive side however, the idea of warmer and drier climate suggests the possibility of milder winters and consequently longer navigation seasons. The impact from lesser carrying capacity could then be counterbalanced by the increase in length of navigation season. An other positive aspect of this scenario could be a less rigorous ice regime resulting in easier transportation and lesser cost in ice breaking.

All in all, however, the resulting impact of a lowered Great Lakes System would be detrimental to the nation's economy.

What needs to be done? Many of the ideas expressed in this paper are personnal and are yet to receive the blessings of the international community. The four eventualities previously articulated and the surmised conclusions that ensued from each one are yet to be agreed upon, particularly the apparently logical assumption that navigation will not be negatively affected by a foot rise in lake level. More importantly, I see an urgent need to accelerate research on the question of cause for the changes in the climate, the source, magnitude and distribution of carbon dioxide into the atmosphere. I see the need to strengthen our international cooperation in the pursuit of an answer, not only as to the "cause" but more importantly the "control of the cause". I see the need to refine the existing models and develop a global model that will mesh together the climatological output with hydrological information to arrive at answers more specific, more finite, for use by the economist, the social scientist and eventually by the decision-maker. When those answers from the climatic models are refined, I see the need after their integration into the hydrologic model, to refine our plans of regulation for the Great Lakes and develop an array of matrices, relating fractions of lake level changes to increments of benefit to navigation.

Most of us here, will have retired by the time precise answers to those salient questions will have been articulated. At least, however, let us get solace from the fact that we have not left it up to the next generation to address the issue. We have opened the box, and have attempted at least to unravel the mystery inside of it.

Conclusion

In an article published by the American Museum of Natural History, dated October, 1987, entitled the Biggest Chill, Dr. Wallace S. Broecker, speaking on this subject made the following statement "Unfortunately, our knowledge of the earth's climate system is still not good enough to reliably predict the effects of this heating on wildlife, agriculture, and a host of other matters important to humans. We will only know the results of the buildup of these greenhouse gases if our learning rate greatly accelerates." Although the necessity to activate research in this area has been articulated before, it is very important to realize how obvious are the complexities and how crucial is the need to unravel the mystery. The greenhouse effect however, being apparently the most manageable of all parameters deserves, in my estimation, a lot of attention. Along those lines, it is very satisfying that the negotiators from thirty (30) different countries who have met last month at the Vienna Convention" for the Protection of the Ozone layer, have agreed to curtail emissions of chlorofluorocarbons (CFC) by 40 to 50% over the next 10 years. Such a cut is critical as those chemicals are deemed to account for 15 percent of greenhouse gases. The scientific exchanges between the United States and the Soviet Union on the subject of climate, are also very encouraging and eventually will help to reduce the impact of the greenhouse effect. Accelerated participation of the Environmental Protection Agency, the Department of Energy (which has been studying the $2CO_2$ problem for more than 10 years now), and the Canadian Climate Center, are also very encouraging. If other processes that trigger changes in the climate are natural or simply part of the evolution of the cosmos, we as humans can and must do our part either by accelerating research to arrive at a more complete understanding of the system or by modifying our attitude in order to be able to take timely action to curtail or eliminate the aggravating factors.

As to the Great Lakes, while we will expect their levels to continue their cyclic variations both during the year and over long periods, we need to keep in mind the impact of the climate in the refinement or development of regulation plans. I mentioned before that the latest geologic studies suggest that the earth's climate system resists change until pushed beyond some threshold, then leaps into a new mode of operation; this is not encouraging insofar as the potential major impacts that such a sudden change would be on the Great Lakes and as decision makers we cannot wait for such sudden change to occur; instead while we remain alert, we must continue to plan as expeditiously as possible hoping that the possible changes will be more gradual rather than sudden, thus allowing time to take corrective action.

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