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EFFECTS OF CHANGES IN STRATOSPHERIC OZONE AND GLOBAL CLIMATE

Volume I: Overview

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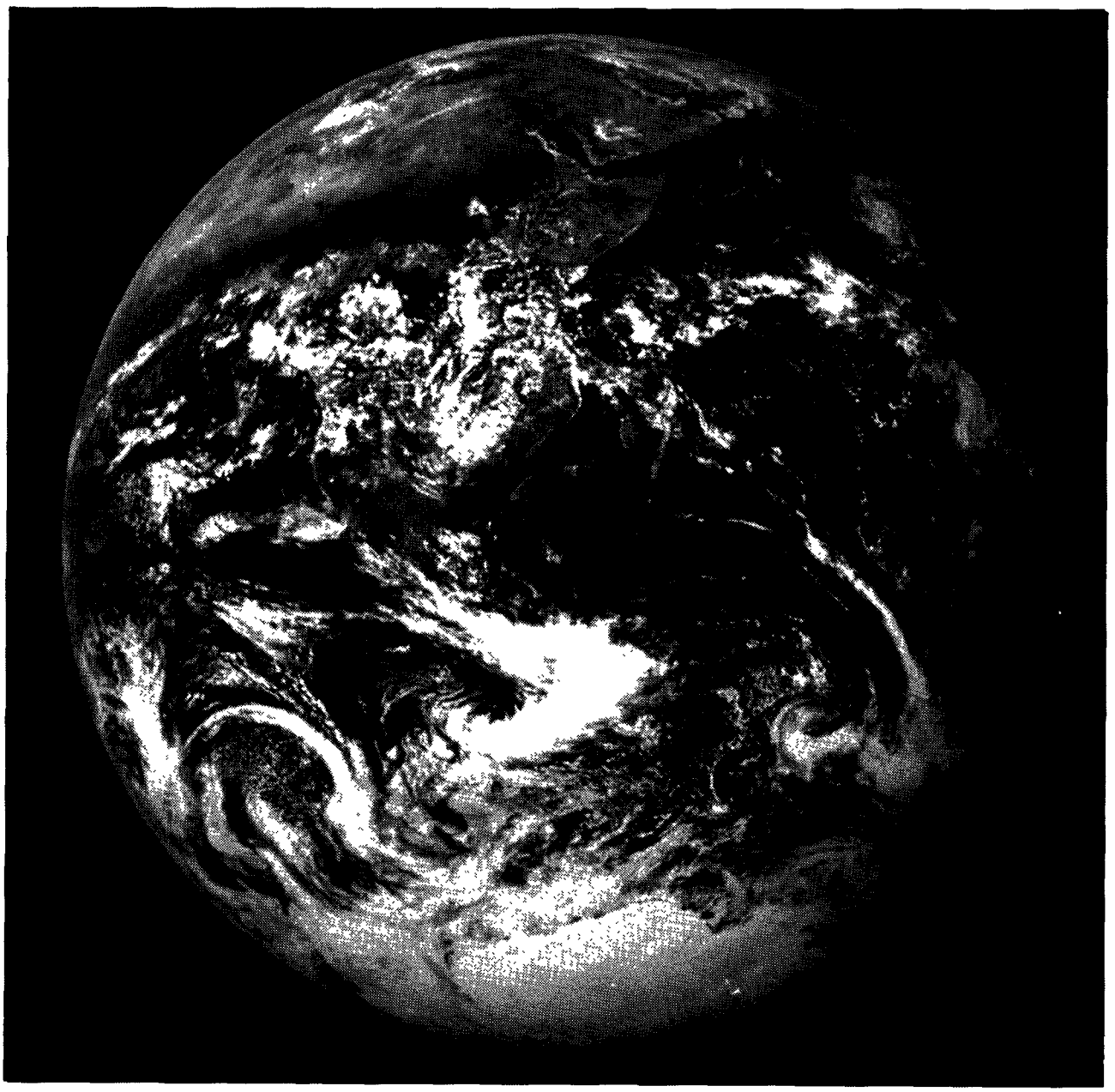

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EFFECTS OF CHANGES IN STRATOSPHERIC OZONE AND GLOBAL CLIMATE

Volume 1: Overview

Edited by
James G. Titus
U.S. Environmental Protection Agency

This report represents the proceedings of the INTERNATIONAL CONFERENCE ON HEALTH AND ENVIRONMENTAL EFFECTS OF OZONE MODIFICATION AND CLIMATE CHANGE sponsored by the United Nations Environment Programme and the U.S. Environmental Protection Agency. The purpose of the conference was to make available the widest possible set of views. Accordingly, the views expressed herein are solely those of the authors and do not represent official positions of either agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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PREFACE

This report examines the possible consequences of projected changes in stratospheric ozone and global climate resulting from emissions of chlorofluorocarbons, carbon dioxide, methane, and other gases released by human activities. During the week of June 16-20, the United Nations Environment Programme and the U.S. Environmental Protection Agency sponsored an International Conference on the Health and Environmental Effects of Ozone Modification and Climate Change, which was attended by scientists and officials from approximately twenty countries from all areas of the world. The four volumes of this report comprise the proceedings of that conference.

Volume 1 provides an overview of the issues as well as the introductory remarks and reactions from top officials of the United Nations Environment Programme and the United States Environmental Protection Agency, two U.S. Senators, and representatives from industry, academia, and environmental groups. Volumes 2, 3, and 4 provide more detailed investigations on the effects of ozone depletion, climate change, and the rise in sea level that might result from a global warming.

We wish to thank the many people who helped us to publish this report on time. Mary Dalrymple and Wendy Martin of Technology Applications, Incorporated (TAI) coordinated a team of copy editors that included Karen Spear, Linda Stiles, June Leatherman, and Susan MacMillan. Sandra Miller directed a team of word processors that included Lynette Dunaway, Felicia Jenkins, and Patricia Maddox. All of these people worked many long nights.

We also wish to thank Maria Tikoff and Stephen Seidel, who coordinated the presentations at the conference and whose perpetually good nature helped keep us enthusiastic, and Judy Salmon of TAI who coordinated the logistics for the conference. Peter Usher of UNEP and John Hoffman of EPA provided overall guidance.

With the exception of the papers by Lee Thomas and Genady Golubev, this report does not present the official views of either the U.S. Environmental Protection Agency or the United Nations Environment Programme.

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INTRODUCTION

Overview of the Effects of Changing the Atmosphere

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INTRODUCTION

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

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

OZONE MODIFICATION

Atmospheric Processes

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

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

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

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

Watson (Volume 1) presents evidence that ozone has been changing recently more than atmospheric models had predicted. As Plate 1 shows, the ozone over Antarctica during the month of October appears to have declined over 40 percent in the last six to eight years. Watson also discusses observations from ozone monitors that suggest a 2 to 3 percent worldwide reduction in ozone in the upper portion of the stratosphere (thirty to forty kilometers above the surface), which is consistent with model predictions. Finally, he presents preliminary data showing a small decrease since 1978 in the total (column) ozone worldwide. However, he strongly emphasizes that the data have not yet been fully reviewed and that it is not possible to conclusively attribute observed ozone depletion to the gases released by human activities. While

there are several hypotheses to explain why ozone concentrations have declined, none have been adequately established; nor did any of the atmospheric models predict the measured loss of ozone over Antarctica.

Ultraviolet Radiation

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

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

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

Effects on Human Health

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

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

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

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

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

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

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

Effects on Plants

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

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

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

Aquatic Organisms

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

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

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

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

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

Polymer Degradation and Urban Smog

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

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

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

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

CLIMATE CHANGE

The Greenhouse Effect

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

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

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

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

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

Water Resources

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

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

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

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

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

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

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

Agriculture and Forestry

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

Parry (Volume 1) provides an overview of the potential impacts of climate change on agriculture and forestry. He points out that commercial farmers plan according to the average year, while family and subsistence farmers must ensure that even in the worst years they can make ends meet. Thus, the commercial farmer would be concerned about the impact of future climate change

on average conditions and average yields, while farmers at the margin would be most concerned with changes in the probability of (for example) a severe drought that causes complete crop failure. Parry notes that the probability of two or more anomalous years in a row could create disproportionately greater problems for agriculture. For example, a persistent drought in the U.S. Great Plains from 1932 to 1937 contributed to about two hundred thousand farm bankruptcies.

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

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

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

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

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

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

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

Sea Level Rise

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

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

actions to curtail emissions or from the thermal lag induced by the oceans' ability to absorb heat.

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

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

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

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

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

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

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

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

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

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

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

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

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

Human Health and Ecological Impacts

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

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

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

POLICY RESPONSES

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

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

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

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

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

Two U.S. Senators also provide their reactions. John Chafee from Rhode Island (Volume 1) describes hearings that his Subcommittee on Environmental Pollution held June 10-11, 1986. "Why are policy makers demanding action before the scientists have resolved all of the questions and uncertainties?" he asks. "We are doing so because there is a very real possibility that society--through ignorance or indifference, or both--is irreversibly altering the ability of our atmosphere to perform basic life support functions for the planet." Albert Gore, Jr. from Tennessee, who has chaired three congressional hearings on the greenhouse effect, explains why he has introduced a bill in

the U.S. Senate to establish an International Year of the Greenhouse Effect. "The legislations would coordinate and promote domestic and international research efforts on both the scientific and policy aspects of this problem, identify strategies to reduce the increase of carbon dioxide and trace gases, investigate ways to minimize the impact of the greenhouse effect, and establish long-term research plans." Senator Gore closes by quoting Sherwood Rowland (discussed below): "What's the use of having developed a science well enough to make predictions, if in the end all we're willing to do is stand around and wait for them to come true?" Both Senators call for immediate action to reduce global use of CFCs.

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

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

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

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

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

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

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

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

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

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

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

We hope that this paper has provided the reader with a "road map" through the papers of this four-volume report on the potential effects of changing the atmosphere. But we have barely scratched the surface of each, just as the existing research has barely scratched the surface in discovering and

demonstrating the possible risks of ozone modification and climate change. A continual evolution of our understanding will be necessary for our knowledge to stay ahead of the global experiment that society is conducting.

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Global Environmental Change: The UNEP Perspective

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It is, perhaps, paradoxical that the global environmental threat, with the potential to influence for good or ill the lives of every individual on the planet, should generate such ambivalent attitudes among people with so much at stake.

It has been constantly said, and will be said again: the global issues are complex; uncertainty exceeds understanding; and patience is prudence.

That coin has another side. The issue, stripped to its essentials, is simple and unequivocal in its message, our legacy to the future is an environment less benign that that inherited from our forebearers. The risks are sufficient to generate a collective concern that forebodes too much to wait out the quantifications of scientific research. Advocating patience is an invitation to be a spectator to our own destruction.

One approach, adopted by the United Nations Environment Programme, aids the selection of an appropriate course of action. This concerns the concept of "outer limits," which postulates that the biosphere has only a limited tolerance to the demands placed upon it.

Two global outer limits have preoccupied UNEP during the last decade: the risk to the ozone layer and the issue of climate change occurring in response to increasing concentrations of trace gases in the atmosphere due to the actions of humanity. Of course, all environmental sectors have an outer limit of exploitation, but in this paper, I restrict my comments to the vulnerability of the atmosphere and its climatic processes to possible changes. The role of this report and the associated conference, as seen by UNEP, can be expressed in terms far beyond a mere exchange of scientific information and viewpoints on the subject of ultraviolet radiation damage or of climatic variability. It is looked upon more as a necessary step in formulating international policy to protect the common atmospheric heritage.

In 1974, the possibility of stratospheric ozone depletion was first noticed. Simple chemical formulae for the catalytic destruction of the earth's ozone shield were unfolded to an astonished world. The repercussions of a weakened ozone layer are as significant as any threat we are ever likely to face. It does not need hyperbole to emphasize its significance for mankind. Human health, fish and animals, plants and food crops are at risk. The principal suspect is the family of manmade chemicals, chlorofluorocarbons, of benign property (at least in the lower atmosphere), and of vast commercial usefulness. The enormity of the issue and the seemingly contradictory results of the scientific examination of the ozone depletion hypothesis have to some extent been counterproductive to attempts to deal with the problem. Ozone depletion estimates have ranged from 5% in the mid-1970s to more than 20% a few years later. Indeed, some scenarios have produced estimates indicating increases in the total ozone column. Such divergences have bred skepticism and fear that subjective and selective interpretation are being introduced into scientific analysis to accommodate rapidly polarizing viewpoints of different nations (and factions) on the problem of the ozone layer. You have read the headlines; perhaps you have even written them: "The ozone problem is no problem" or "The end of the world is nigh."

I am happy to report that UNEP, at least, kept its head in the midst of controversy and, supported by its Governing Council and most of the international community, established a program of activities that has, in the shortest possible time, led to a unique milestone in the annals of international legislation: the Vienna Convention for the Protection of the Ozone Layer. This covenant represents an agreement among nations to act in concert to address an environmental issue still awaiting scientific confirmation of its actuality. Impressive as this agreement is, it remains a tenuous response to the potential threat posed by a changing ozone layer. In present form, it represents an agreement to cooperate in research and in monitoring the ozone layer and other gaseous constituents of the atmosphere and in information exchange regarding production, emissions, usage, trade, and national legislation on substances suspected of modifying the ozone layer. It does not bind states to observe limits in production and emission of these substances, which will require a specific protocol to the Convention and for nations to be party to both the protocol and the Convention--a thorny path still to be negotiated.

Let us look briefly at the program UNEP is operating regarding the atmosphere, which will explain the reason why it cosponsored the "Effects Conference" and this report. In 1977, in response to calls for a rational approach to the ozone layer issue, UNEP convened an International Conference on the Ozone Layer in Washington, D.C. A main purpose was to elaborate a world plan of action on the ozone layer. Under the plan, coordination of the research effort was to be the province of UNEP and, to assist it in this task, UNEP established a Coordinating Committee on the Ozone Layer (CCOL) composed of international, governmental, and nongovernmental organizations with active ozone layer research programs. This committee makes and publishes through UNEP, assessments of ozone layer modification and its impact based on national research results reported to it. To date, the CCOL has met eight times to refine its estimate of projected ozone layer change. As I noted above, the

CCOL's predictions have shown wide variations from year to year. Over the last five years, predictions have moved in a much narrower range and even the most skeptical of governments accept the validity of UNEP's approach to the problem.

I have referred to the UNEP role as coordination and catalysis. I might add that the UNEP approach to an environmental problem is to assess the nature and scale of the issue and, based on the assessment, to provide advice on the range of managerial options available to address the problem. In the case of ozone, the assessment is a continuing one and one that has yet to resolve the many uncertainties that still exist. Let us not minimize these uncertainties: A statistically significant depletion of ozone has been observed at 40 km consistent with the theory of ozone modification. Yet we may still be a generation away from finally confirming or denying ozone modification as fact.

The assessment of the physical state of the atmosphere and, in particular, of the ozone layer, has taken a giant step forward over the past year and a half. Nine national and international organizations cosponsored and cooperated in a giant--there is no other appropriate word--assessment orchestrated by the U.S. National Aeronautics and Space Administration (NASA). The CCOL drew on this assessment to make its own estimation of ozone layer change. The committee did not, however, address the issue of effects of ozone layer modification. UNEP will next arrange for the summarizing of the conference findings by experts for consideration by government experts at a special session of the CCOL later in 1986 with a view to preparing an assessment of impacts of ozone layer depletion equivalent to that already produced on the physical ozone layer.

But assessment, in the UNEP context, is to be followed by rational environmental management. An ad hoc working group of legal and technical experts was convened by UNEP in 1982 and met seven times before agreeing on the framework for an international convention for the protection of the ozone layer. This group is now to be reconvened to determine the need for and the form of a protocol of chlorofluorocarbons to the Vienna Convention. Technical information on chlorofluorocarbons will become available from a two-part workshop on aspects of production, use and release of those chemicals, and the consequences and policies of their control. The first workshop took place in May 1986 in Rome. The second part will be in Washington, D.C. in September 1986.

If there is need of a protocol on CFCs, the Vienna Group, for that is how it is known, will determine it; hopefully, the agreed protocol will be adopted by diplomatic conference in 1987.

It is a long road, full of pitfalls, demanding goodwill and indeed sacrifice in the form of agreements to limit national industrial activity, trade, and a loss of convenience that CFCs currently provide. Forget the frivolous cosmetic aerosol use of the chemicals--refrigeration, rigid and flexible foams for insulation, packaging and upholstery, solvents for the electronic industry, and pharmaceutical products also depend on the CFC industry. More than thirty-five million tons of these non-toxic, non-reactive, convenient gases have already been emitted to the atmosphere to

remain there for tens or even hundreds of years. Each molecule has the potential to dissociate as many as four hundred of the essential ozone molecules in the fragile shield protecting us from the ravages of unrestrained ultraviolet radiation.

The Convention was a necessary and timely precaution and UNEP will encourage any measure--such as the elaboration of suitable protocols--that will ensure its effectiveness in protecting the environment.

I believe that the goodwill of most nations supports UNEP in its objective; but it needs more than goodwill. Adherence to the spirit as well as to the letter of the Convention and its protocols will be necessary prerequisites for its effectiveness. My concern here arises from a request by UNEP for factual data on current production capacity, production, emissions, use, and regulatory measures concerning chlorofluorocarbons to all member states of the United Nations, all regional economic groups, and relevant non-governmental organizations. The purpose of the request was to make available necessary background information to the Workshop on Chlorofluorocarbons. The response was extremely poor. Only twenty relevant replies were received out of the more than 170 requests sent. It hardly provided a representative sample of the nations involved in the chlorofluorocarbon industry--hardly enough to promote useful analyses of the use, trade, and emission patterns. Probably all countries use CFCs even if they do not manufacture them. After all, the substances are widely used in refrigeration and air conditioning. Can the lack of replies be attributed to ignorance of the extent of trade and use in CFC containing products, to the designation of low priority to the issue by states with more pressing environmental problems begging attention? UNEP will do all it can to raise the consciousness of individuals and nations to the potential gravity of the situation. But meanwhile, the ozone problem is still "up in the air." The improvement of scientific knowledge is the responsibility of you, your fellow scientists, and others who care for our environment.

I have focused on the ozone layer problem mainly because it is at the center of an intense effort by UNEP at the present time; but it is not the only global issue receiving the attention of the international community. Nor even is the ozone issue a problem addressed independently of other atmospheric environment problems. UNEP is active in the fields of long-range transboundary air pollution, acid deposition, and the greenhouse effect climate change issue. Carbon dioxide is generally regarded as the agent of climate change; but ozone, projected to increase in the troposphere, and ozone modifying gases, such as methane and the ubiquitous chlorofluorocarbons, are also greenhouse gases. Despite their relatively low concentrations compared with carbon dioxide, some are vastly more efficient absorbers of infrared radiation than CO_2. UNEP operates a major program on the greenhouse gas issue, parallel and closely interwoven with the ozone layer program. Indeed, action to protect the ozone layer, for example, by limiting emissions of chlorofluorocarbons, will surely have a profound impact upon the rate of climatic change.

If anything, the climate change issue is more resistant to solution than ozone modification. Although there is already scientific consensus on the probable future consequences of doubling carbon dioxide or its equivalent in other greenhouse gases--at least in the global sense--the understanding of regional climatic change is closer to speculation rather than scientific

prediction. Nevertheless, preparations for a future climate change need to begin now and UNEP is developing a program that will address the socioeconomic consequences of climate change and of the range of policy alternatives that governments might consider in response. Whether there will be a need for a future legislative process similar to that developed under the Risks to the Ozone Layer Programme is not yet known. One major difference between the two issues is that the consequences of ozone depletion are universally harmful; climatic change, on the other hand, will provide benefits to some as well as disadvantages to others. Some countries, for instance, those with densely populated low-lying coastal areas or with agricultural areas postulated to receive less rainfall, may be big losers. Increased rainfall or longer growing seasons in the present marginal areas for crop production can only be greeted with delight by the affected countries. Again, while regulations of the emissions and use of CFCs are likely to be relatively easy, the price of regulating CO_2 emissions through energy controls may be too high a price to pay, and the future lies in adaptation to rather than in prevention of climate change. UNEP's present role in this issue is the provision of international assessments. It does so in cooperation with its partners, the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU), the three organizations that implement the World Climate Program. In October 1985, UNEP, WMO, and ICSU held a second conference on the issue at Villach, Austria, where a new assessment of the issue was made (the first was also made at Villach, five years earlier).

A recommendation of the Conference is the establishment of an Advisory Group on greenhouse gases, composed of a small group of eminent scientists, to advise the international organizations on a program to address the greenhouse gas/climate change issue. This group of "seven wise men" will meet in Geneva during the first few days of July. However, no matter what program they suggest to the international community, it will again require an enormous complementary scientific effort. Most importantly, there is need of a partnership of effort involving all nations to consider the consequences of greenhouse gas-induced climate change and to respond in concert to provide whatever solution may be required.

In the face of these global issues, the world's commitment to the environment is on trial. I trust in the final analysis that commitment will not be found wanting.

Global Environmental Change: The EPA Perspective

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This report focuses on two global environmental problems that might result from the worldwide emissions of certain gases: the depletion of stratospheric ozone and a global warming from the "greenhouse effect." Both issues are clear examples of a "global commons" environmental problem. All nations are responsible for contributing to recent changes in our atmosphere--although the industrially developed nations must shoulder most of the responsibility. All nations will be affected by depletion of the ozone layer and by global climate changes.

Based on our current understanding, we believe that a small change in the amount of UV-B radiation striking the earth and/or a change in the earth's mean temperature could have significant environmental and health consequences. The fundamental scientific uncertainty is no longer "are these phenomena real?" but rather, "at what rate are they likely to occur?" We need to better understand the full nature of the impact of these changes and the possible options, both in the near and long term, for managing these risks. We do not yet have complete answers to these questions, although recent efforts have resulted in substantial progress.

It was only after extended discussion and considerable thought that the United Nations Environment Programme (UNEP) and the Environmental Protection Agency chose to proceed with a conference on both ozone depletion and climate change. As the other papers in this volume show, our understanding of atmospheric science tells us that ozone depletion and global warming are inexorably interconnected. However, the domestic and international politics surrounding each issue are separate and unique. Combining the two in one conference had the potential to confuse and compound the political controversy surrounding each issue. Separating the issues would fail to address their physical interdependence. In the end the choice was clear: we resolved this issue by recognizing that this conference is first and foremost a scientific meeting, not a political one, and therefore it should be organized around our understanding of the science.

As a scientific meeting our objective was not to find solutions to the problems but rather to do the best we can to organize and present the current state of science. In trying to achieve this goal the conference was not an isolated event but part of a sequence of environment meetings intended to systematically build our understanding of these problems.

In October 1985 in Villach, Austria, atmospheric scientists and government officials prepared a major document summarizing the scientific consensus that is gradually emerging regarding the greenhouse effect. That conference, sponsored by the World Meteorological Organization (WMO), the International Council of Scientific Unions (ICSU), and UNEP, provided a sound scientific foundation for this report's discussion of the effects of global climate change.

In February 1986 in Nairobi, Kenya, UNEP sponsored a meeting of the Coordinating Committee on the Ozone Layer (CCOL) to explore the state of knowledge on the atmospheric science of ozone depletion. A text was unanimously adopted based extensively on the NASA Assessment Report. The CCOL Report and the NASA documents both serve as the foundation for this report's discussions on the effects of ozone depletion.

Finally, in May 1986 in Rome, UNEP held another meeting that focused on projections of future chlorofluorocarbon production and emissions. Information from that meeting will help us to address the problem of ozone depletion.

This sequence of meetings is no accident. Each meeting is part of a conscious effort to build a common understanding among the nations of the world about the nature of these problems before we sit down to talk about possible solutions. At the U.S. Environmental Protection Agency, we recognize that it is important to separate the process of risk assessment from the decision-making task that we call "risk management." Risk assessment refers to the gathering of scientific data in order to understand what type of problems may confront us if we fail to intervene. Risk management refers to the evaluation of options to avert those potential problems. Although various interests may have different points of view regarding the level of action that may be appropriate, it is my strong belief that the process will be more constructive if everyone works from a common understanding of the scientific facts. We rely on the separation of these tasks as a basic approach to most of the major environmental decisions. Before we can sit down together to find a common solution to a problem, we must first have a common understanding of the problem we are trying to solve.

In the last decade we made major advances in assessing the risks of ozone depletion and the greenhouse effect. This report presents and summarizes the major portion of our understanding of these two problems.

However, before we move too quickly into the task of risk management I must raise a word of caution. If the risk management part of the process is to work effectively, environmental policy-makers from each of our countries must be made aware of and understand the science involved in these issues. If not, then much of the progress we have made in developing a common understanding of those problems will be lost. It serves no useful purpose to have decision-makers like myself approach problems such as these with either

an inflated or deflated view of the problem, and it is only through the patient but persistent efforts of the experts that decision-makers like myself can get the facts we need to make intelligent decisions. I urge the reader to actively share this information with your colleagues and key officials. Tell them what we know, what we don't know, and what we are likely to understand soon. Let them know where we have consensus and where we disagree. Let me also ask you to share with us your data and scientific information.

In the U.S. we are still gathering the facts; we are still in the role of risk assessor. Domestically, we have committed ourselves to making a decision on the need for further regulations of CFCs in the fall of next year, and we have committed ourselves to actively supporting and participating in the Vienna Convention process for the protection of the ozone layer. Our commitment to this process should not be seen as a precedent to a particular outcome. At the same time we have not made any decisions either as to the need for additional domestic regulation or the content of an international protocol. In both cases we will wait until we have completed the risk assessment, before we make the risk management decision.

We recognize that several important facts must not be overlooked. To the extent that action is needed, it is essential that the international community move forward to deal with these issues together. Our analysis must include all trace gases that may modify the ozone layer and not just CFCs. CFCs are extremely important chemicals used across a broad spectrum of industrial and consumer goods. For some uses, no effective alternative chemical currently exists. Finally, the potential risks we face are generally long-term; if action proves warranted, any regulatory approach selected should be structured in a way that minimizes costs and disruption to producers and users.

I am deeply concerned about the potential environmental risks associated with these issues and the complexity of developing a response that effectively addresses their unique characteristics. Despite these complexities, we are moving forward in a timely manner to responsibly address these issues. I am committed to making a decision even in the face of the many uncertainties that are likely to persist for the next several years.

Global Environmental Change: The International Perspective

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As a career diplomat who deals with scientific issues, and who strongly believes in their growing relevance to foreign policy, I appreciate the opportunity to present my views. I will briefly sketch how the international community can confront such complex, long-term issues as global climate change and ozone layer modification.

International law is relatively well equipped for dealing with trans-boundary environmental problems, where one nation can be identified as "the polluter" and the other as "the polluted." But in the case of global environmental problems, such as ozone depletion and climate change, the international community is in fact entering uncharted territory.

This emerging set of problems contains a number of unique elements. First, almost every nation is both perpetrator and victim: many nations are producers and/or consumers of chlorofluorocarbons (CFCs), most nations burn fossil fuels or otherwise emit carbon dioxide, and all nations will be affected by ozone depletion and climate change. Secondly, the adverse impacts, and the costs of mitigating those impacts, are not distributed equally among nations--nor necessarily in proportion to each nation's contribution to the problem. Finally, for both ozone depletion and climate change the time-lag between cause and effect spans decades--which is longer than the normal policy-making horizon of most governments.

Given these factors, designing an efficient and equitable control system would be exceedingly difficult, even as a theoretical exercise; in practice, a new paradigm for international cooperation likely will be needed.

But what form might this paradigm take? To answer this question, I think it would be useful to look at international activities of the last decade that relate to the ozone depletion issue and--with the benefit of hindsight--to reflect on what has worked and what has not.

International attention to the question of stratospheric ozone depletion began shortly after Rowland and Molina published their now-famous theoretical paper. A number of international meetings were held on this subject during the late 1970s, at the same time as several nations began to issue domestic CFC regulations. In 1980, the Governing Council of the United Nations Environment Programme decided to convene a Working Group of Experts to discuss appropriate international action to address this potential problem.

The UNEP Working Group decided early in their deliberations to develop a convention--that is, an international treaty--on the ozone layer. Four years and several long negotiating sessions later, they completed their work on such a treaty. In March 1985, at a Plenipotentiary Conference in Vienna, Austria, where I represented the United States, twenty-one nations signed the Convention for the Protection of the Ozone Layer. This was a landmark event: it was the first time that the international community acted in concert on an environmental issue before substantial damage to the environment and health was done--in effect, acting together in anticipation of potential problems.

The "Vienna Convention" creates a framework for international cooperation on research, monitoring, and information exchange concerning the ozone layer. It also creates general obligations to protect the ozone layer and provides procedures for eventually adopting protocols to the Convention, which could contain specific measures to control, limit, prevent, or reduce emissions of ozone-modifying substances--should such measures be deemed necessary. In the United States, the Senate has held hearings on the Convention, and we expect it to be ratified soon. After twenty nations have ratified it, the Convention becomes international law.

The question of a control protocol was the subject of considerable debate during the UNEP Working Group negotiations. In April 1983, Norway, Finland, and Sweden tabled a draft protocol for controlling all CFC uses. In October 1983, the United States voiced its support for that part of the "Nordic Proposal" dealing with CFCs used as aerosol propellants. Eventually the Nordics, along with Canada and Switzerland, joined us in supporting an international aerosol ban protocol.

On the other side of the debate, the nations of the European Economic Community--who represented the other major source of CFC production--were initially opposed to any further controls on CFCs. However, they eventually supported a protocol--but, like us, and not surprisingly, they supported one that mirrored what they already had in place: a 30 percent reduction in aerosol use and a cap on future CFC production capacity.

During the debate on these two alternative control approaches, we pointed out many of the problems with their approach, and they in turn noted many of the flaws in our approach. The result was total gridlock, and there was no possibility for agreement on a protocol text at the Vienna Conference.

However, because most of the disagreement near the end of the negotiations had centered on the economic and policy aspects of alternative control strategies, participants generally agreed that a series of international workshops--outside of a formal negotiating context--would be useful to these questions in detail. All parties also agreed to approach these workshops with an open mind, unwedded to their previous negotiating positions. This

certainly represents the U.S. position: we are prepared to re-examine the costs and benefits of various protocol options, ranging from no further controls to a full cap on production or use.

The first international workshop was held in Rome during the last week of May 1986. A second international workshop was planned for September 1986 in the United States to evaluate alternative strategies for international control. After the workshops, the next round of protocol negotiations was planned for November 1986, with a second Diplomatic Conference scheduled for April 1987.

Scientific assessments are proceeding on a parallel track: earlier in 1986, the National Aeronautics and Space Administration (NASA), the World Meteorological Organization (WMO), UNEP, and other organizations completed two years of work on an international assessment of atmospheric processes. The UNEP Coordinating Committee on the Ozone Layer met in January 1986 to review the state of the science and will meet again in August. The International Conference on the Effects of Ozone Modification and Climate Change further contributed to this process.

Where have we come on the ozone layer internationally? Looking back with the benefit of hindsight on the past round of negotiations, I believe that the international community may have tried to put the cart before the horse: we were trying, in effect, to make a risk management decision before conducting a risk assessment.

The first part of this approach, risk assessment, involves identifying the range of potential adverse effects and the affected population, estimating the timing and magnitude of those effects, and assessing the attendant uncertainties. The second step, risk management, entails developing a set of possible regulatory options, analyzing the efficacy of these options in reducing the risks identified, evaluating the economic and social costs and benefits of the various options, and then choosing the most efficient option.

Some of the virtues of this approach are that it recognizes cost/benefit analysis as an integral part of decision-making, but it separates such analysis from assessment of the risk. It recognizes the need to assess scientific and other uncertainties, but it does not allow the existence of uncertainties per se to automatically stop the decision-making process.

The two-part UNEP workshop uses a format similar to that prescribed by the "risk assessment-risk management" approach. As far as I am aware, this is the first time that such a process has been deliberately established at the international level and, as such, it is truly an innovative approach.

Whether this approach will work is at this point an open question. A primary aim of the first part of the workshop was to try to find a reasonable range of estimates of future growth in CFCs and the other trace gases, which could then be plugged into the various global atmospheric models to give us estimates of the timing and magnitude of ozone depletion.

The Rome workshop was only partially successful in this regard. Although I wasn't there, I gather that the Workshop's limited success was due in large part to the view of some delegations that because making future projections

inherently entails uncertainties, nothing can be said about the future. The pitfalls inherent in this kind of all-or-nothing thinking should be obvious. For example, the notion that "future risk cannot be estimated with certainty" is sometimes translated, by a curious leap of faith, into the assertion that "there is no future risk"--when that may not be the case!

We should suspend judgement on whether this approach can in fact work on the international level until after Part II of the Workshop. However, if it does work, I believe that the international community could adopt this paradigm in order to come to grips with the issue of global climate also.

As noted at the UNEP/WMO/International Conference on Scientific Unions (ICSU) Conference on Climate Change last fall in Villach, Austria, it is well established scientifically that the earth's average surface temperature will rise as the result of increasing concentrations of "greenhouse" gases. But how much warming will occur, and when, is less certain. And what global warming will mean for regional temperature and rainfall patterns is still very much uncertain.

Our knowledge of the impacts of climate change is thus a few years behind that of ozone depletion. It is therefore probably too early for the kind of structured workshops that we are undertaking with respect to the ozone layer issue to be undertaken to deliberate climate change. In the meantime, I believe that we should follow the Villach Conference recommendation to give higher priority to researching and assessing the impacts of climate change.

From my perspective as a career diplomat, it appears that the greenhouse effect has all the markings of becoming a high visibility foreign policy issue. The time scale between cause and effect, between policy action and desired result is distressingly long. Somehow, political leaders and government processes and budget makers must accustom themselves to a new way of thinking. The scientific issues are complex, interrelating many different scientific disciplines, often at the frontiers of discovery. The uncertainties are still a subject of debate. How we address this issue internationally depends to a great extent on our success or failure in dealing with the ozone depletion issue. And how we deal with global climate change may in turn influence how we deal with other similar international issues.

Thus, the activities in which we are engaged--including this report and the International Conference on the Effects of Ozone Modification and Climate Change--are of no small consequence to the world. I wish these efforts success and wise counsel.

Man's Impact on Earth's Atmosphere

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The astonishing thing about earth is that it is alive in a corner of the cosmos where all other bodies are lifeless. This was never more dramatically demonstrated than 17 years ago, when men first walked on the moon and sent home those marvellous photographs of earth-rise over the dead moon. Our beautiful planet home is blue with water, green and brown with vegetation and land, and wreathed in bands of white clouds of our atmosphere. This atmosphere, "as thin as the dew on an apple" (Watson 1984), makes the rest possible.

We now know that our species has the capability of modifying, in a major way, the constituents of the atmosphere and the climate it produces. We have inadvertently assumed a great responsibility. If we are to continue to alter the atmospheric balances, we should be sure we can predict and understand the consequences and be sure that these changes are tolerable.

REGIONAL ATMOSPHERIC CHANGES

More than three decades ago, the great climatologist R. Geiger (1950) wrote: "the blue sky laughs over the landscape, while in the city all is covered with grey and the sun shines along with a weak yellowish-red light. Outside, it is possible to see church towers several kilometers away; inside, the houses on long streets soon disappear in impenetrable grey. The larger the city, the denser, heavier and more resistant is its haze hood."

Thirty-five years after Geiger's observations, the Organization for Economic Cooperation and Development (OECD 1985) was able to list twenty-one cities in its industrialized member countries where the situation had changed drastically. In these major cities between 1975 and 1983, sulphur dioxide concentrations have declined by 19% to 65% (the latter figure for Newcastle and Oslo), with only one, Rome, showing an increase in concentrations. Similar trends are evident in concentration of carbon monoxide and particulate matter, but trends are not so positive for nitrogen oxides and photochemical oxidants, such as tropospheric ozone.

These reductions have been achieved by enforcing pollution control measures; by reducing economic activity over the measured period in the heavy, most polluting, industries; and by building higher stacks to carry the airborne wastes beyond the cities. So while the air quality in our cities has generally improved, there has been a growing realization that much of this improvement may be causing contamination of a large part of the earth's atmosphere as well as environmental damage in the countryside far removed from urban centers. How much the situation has deteriorated in the regions away from cities is difficult to tell, since very few measurements of rural air or precipitation quality go back before the 1970s.

However, we do know that some of the effects of airborne pollutants on lakes and soils are cumulative year after year; we know that many chemical species are increasing in the whole global atmosphere; and we know that stagnant weather conditions, with high pressure systems over the industrial regions of Europe and eastern North America, result in "megalopolitan plumes" of smog that can blanket half a continent. With these newer perceptions, much of the scientific and regulatory attention on air pollution has shifted from the cities, becoming global and regional in scale. We are now concerned about what Watson (1984) has called the "international trade in pollutants" brought about by "the democracy of world winds."

We are altering the chemical balances of the earth's atmosphere and the relationship between our veil of air and the earth's biological systems. These biological communities, which sustain our species, have grown in harmony with the air we breathe. Or if you are a follower of Lovelock and the Gaia hypothesis, the biota have largely created the atmosphere, over the millenia, with a chemical composition designed to sustain the life forms of earth. But we are upsetting the balances in a relatively short time. What are some of the ways our activities have been changing the air we live in and what are some of the consequences?

PRECIPITATION CONTAMINATION AND EXCHANGE WITH WATER BODIES

At a conference on the Great Lakes in 1970, I felt justified, after reviewing some data on chemical contamination of precipitation of the basin, in saying that it was no longer a compliment in Toronto to say that a woman was "as pure as the driven snow." Chemical composition of precipitation reflects contamination that is carried by the winds for both short distances and distances of thousands of kilometers. Furthermore, evidence of serious contamination of the rain and snow has accumulated alarmingly over the past 15 years.

The major concern of the media, and with justification, has been acid rain, a problem in large regions such as eastern North America and Europe, and an increasing global concern. The pH of "clean" rain is about 5.6 with present CO_2 concentrations in the atmosphere. But major areas of the Northern Hemisphere have been experiencing for some years--probably decades--precipitation with acidity averaging lower than 4.6 and as low as 4.2--ten to forty times as acidic as "clean" rain. The main contributor to the suite of acids is sulphuric acid derived from sulfur dioxide (SO_2) emissions from thermal power plants and smelters. The relationship between low pH areas and high sulfate deposition is very strong in Europe and eastern North America.

The data from the Background Air Pollution Monitoring Network (BAPMoN) of the World Meteorological Organization, part of the Global Environmental Monitoring System (GEMS) sponsored by the U.N. Environment Programme, has been used to assess the sulfur in precipitation on a global scale. The areas with average values greater than 1.5 to 2.0 mg/l in 1980-82 include eastern North America; much of Europe; central USSR on both sides of the Ural mountains; a region in the Far East over eastern China, Japan, Taiwan and the Philippines; the east coast of South America between Sao Paulo and Rio de Janeiro; and a smaller less well documented area in southern Africa. It is hardly surprising that high rates of sulfur deposition in rain and snow are becoming nearly global, if one considers the tenfold increase in anthropogenic sulfur emissions since 1900 (see Figure 1).

The acidification of unbuffered lakes is of course closely related to sulfur deposition. Many lakes in Canada, the northeastern USA, and Scandinavia have become too acidic to sustain fish. Recent findings that the droplets at the base of clouds and in some fogs, for example in Japan, are often ten times as acidic as the rain have generated concern about damage to forests and vegetation at high elevations that are frequently shrouded in clouds and fog for long periods.

But it is not just acidic substances that are contaminating the rain; toxic metals and organics do so as well. The next newspaper headlines will probably feature "toxic rain." For example, atmospheric loadings of toxic contaminants are known to be the dominant source of some pollutants in the Great Lakes, particularly PCBs, lead, zinc, and copper (see Figure 2).

Recent evidence suggests that in addition to being a source of toxic contaminants for the lakes, the atmosphere is also a "sink," at least temporarily, for toxic substances volatilized to the atmosphere from the waters (see Figure 3). In fact, recent studies of the budget of chlorinated benzenes introduced by the Niagara River into Lake Ontario suggest that more than 80% of these compounds are volatilized into the atmosphere. As much as 50% of the PCBs that get into Lake Ontario water may return to the atmosphere by volatilization. What is most disturbing is that measurements of a highly toxic contaminant such as Mirex, known to have been only discharged directly into Lake Ontario waters, have been measured in crops, cattle, and milk from land areas surrounding the lake. These represent a far more important vehicle by which toxic chemicals are likely to be consumed by most people living in the basin than the fish and treated drinking water. Thus, the scientific questions of the volatilization processes and their implications for the toxic chemical budget of the region are under intensive research.

GLOBAL ATMOSPHERIC CHANGES

These problems of contamination of rain by acidic and toxic substances, while gradually becoming global, tend to be concentrated regionally. However, there are a number of atmospheric contaminants that have a nearly uniform worldwide distribution and are beginning to have global effects, particularly on the earth's climate, on the vertical temperature distribution of the atmosphere, on stratospheric ozone, and on the total amount of ozone in a column above the earth at any location. These increases in contamination of the earth's atmosphere are probably decreasing the health-protecting ozone layer and can cause an unprecedented global warming. Let us review, briefly,

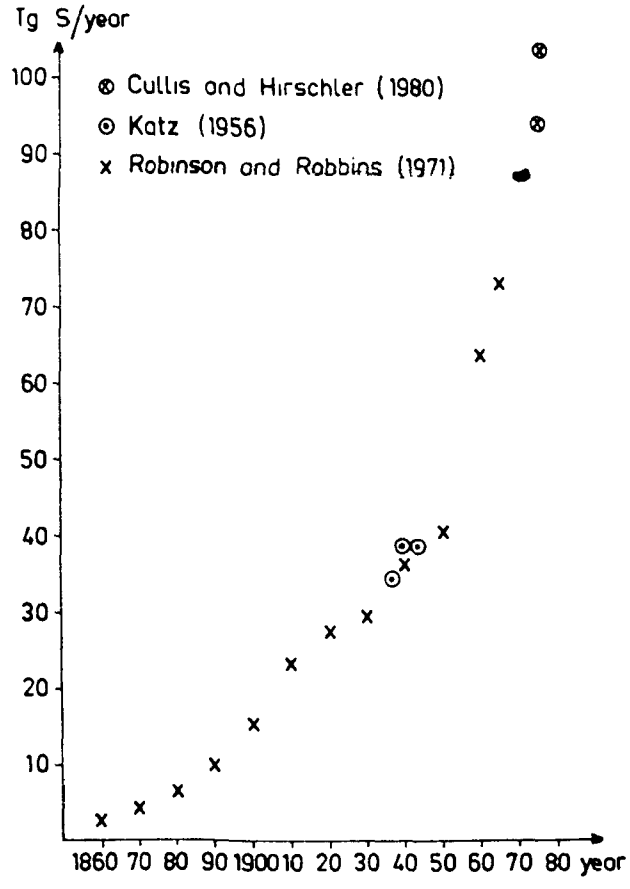
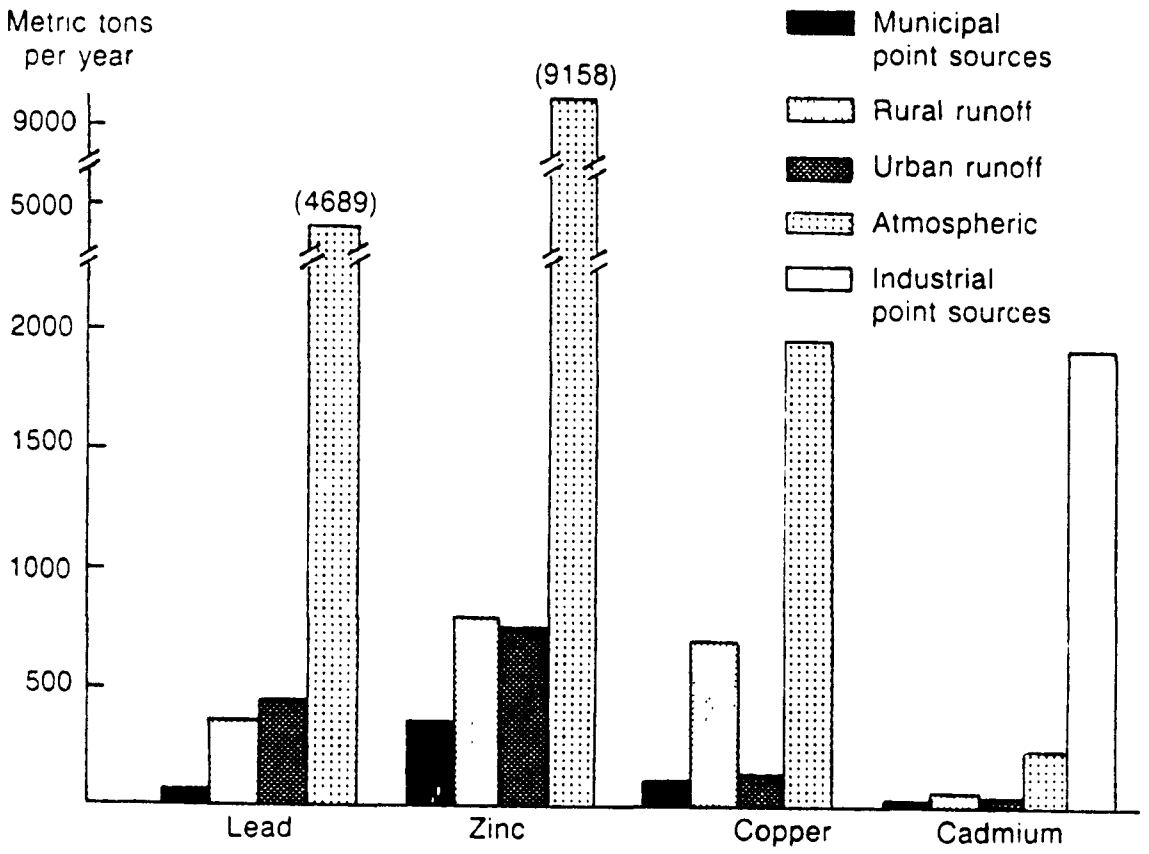


Figure 1. Estimates of Global Anthropogenic Emissions of Sulfur into the Atmosphere (millions of metric tons per year)



Industrial loadings are not indicated for lead, zinc, and copper.

Figure 2. Metal Loadings to the Great Lakes, by Source

Source: Great Lakes Basin Commission and
Great Lakes Science Advisory Board

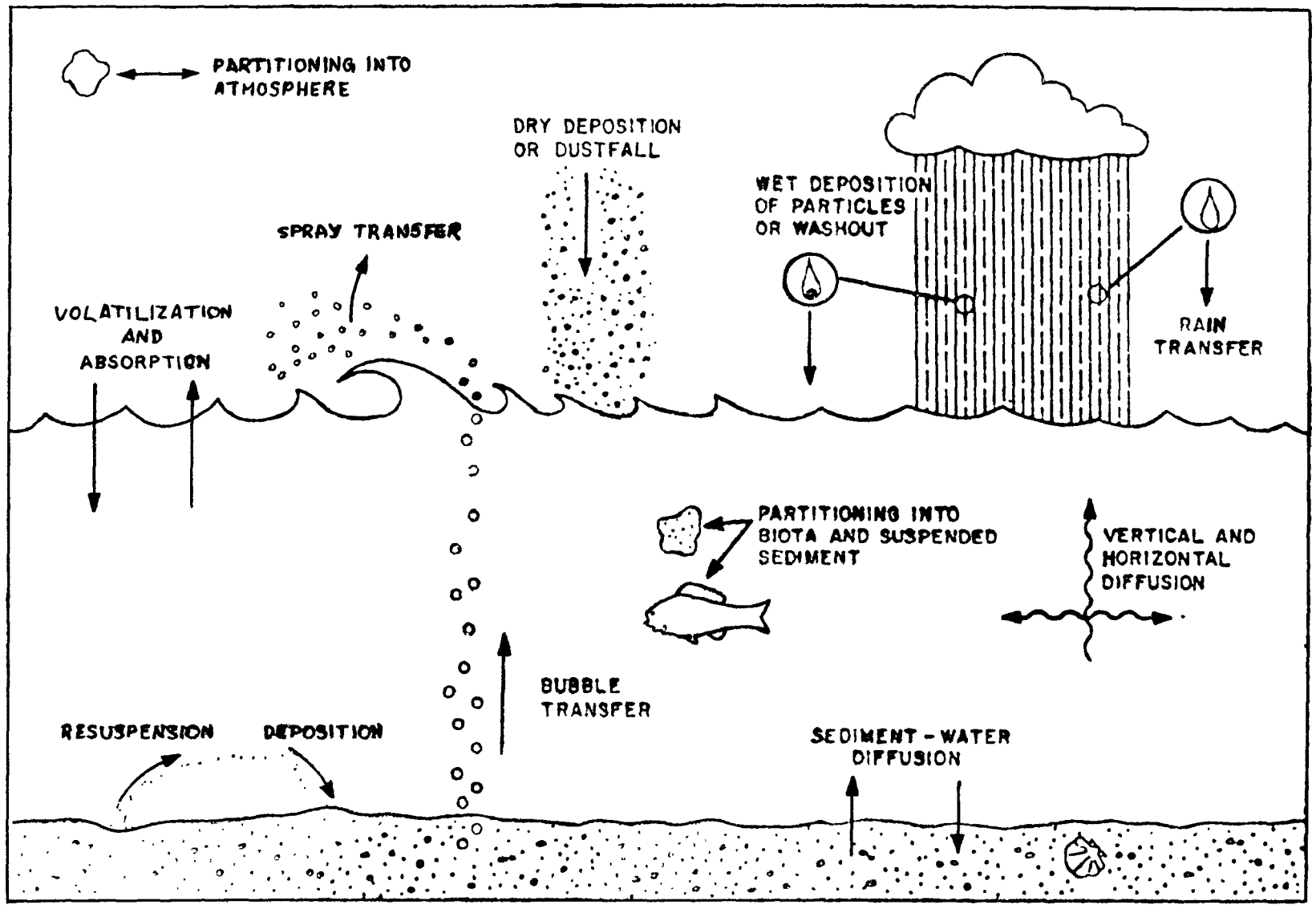


Figure 3. Air-Water Exchange Process

Source: Atmospheric Environment Service, Environment Canada

some of the wonderful things humanity has achieved so far in changing the air around us.

The substances of primary concern in bringing about ozone and climate changes are carbon dioxide (CO_2), the chlorofluorocarbons (CFCs), methane (CH_4), and the nitrogen oxides (NO_x). These are all increasing on a global scale and current annual rates of increase in the atmosphere are very large. The most important of the CFCs are increasing at 5% to 7% per year; CO_2 is increasing at about 0.5% per year and methane at about 1%. To compound the problem, the residence times of some of these gases are very long; $CFCl_3$, CF_2Cl_2, and nitrous oxide remain in the atmosphere 75 to 150 years. CO_2 remains even longer. These long lifetimes imply that annual increases are cumulative over a long period of time and that any changes in climate or ozone distribution brought about by such substances will last for centuries even if remedial actions are taken.

To complicate matters, other gases introduced into the atmosphere by human activities or formed in the atmosphere by reactions involving anthropogenic substances also have direct or indirect effects on temperatures and on ozone formation or dissipation. These include the hydroxyl radical (OH), which reacts with carbon monoxide (CO) and methane (CH_4). With increases in both CO and CH_4 the cycle between these gases and the hydroxyl radical may be reducing OH concentrations, and thus the capacity of the troposphere to remove many gases may be reduced.

The increase in methane concentrations is particularly interesting because of difficulties in determining why it is occurring. The data on the upward trend summarized in Figure 4 indicate a 1.1% increase per year between 1976 and 1985. Methane concentrations are affected by natural microbiological processes in water-logged soils and in the intestines of herbivores, and by industrial activities involving the use of natural gas, burning of biomass, and burning of coal. Figure 5 (Bolle, Seiler, and Bolin 1985) shows the probability that increases in atmospheric CH_4 are caused by both industrial activities and society's impact on natural processes. The figure shows the close parallel between world population trends and CH_4 mixing ratios for the past 600 years, as determined from ice cores in Greenland. Table 1 gives estimates by various workers of the range of values of emissions from the various sources. Increasing numbers of ruminants and rice paddies, as well as biomass and natural gas exploitation, are the main sources of increased methane in the atmosphere. Increased methane concentrations will certainly add to the greenhouse effect, but may also decrease chlorine (Cl) concentrations in the stratosphere, which would slightly reduce the rate of ozone depletion resulting from CFC emissions.

Nitrous oxide (N_2O) is also increasing in the atmosphere but at a considerably slower rate. The source is primarily microbial processes in soil and water, with both denitrification and nitrification contributing to release of N_2O. Production is enhanced by application of fertilizers of mineral nitrogen, especially ammonia-based fertilizers, and from increases in the use of lands for agriculture. Both sources are significantly affected by farming activities. Natural processes in the oceans and fossil fuel burning are also N_2O emission sources. Global emissions over the past century have increased about 55% (see Figure 6). In addition to its relatively small effect as a

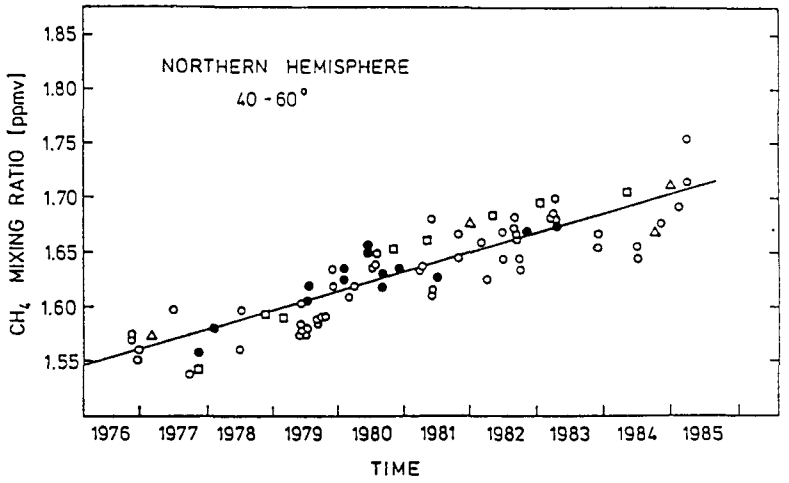


Figure 4. Trend of tropospheric CH_4 mixing ratios (concentration) observed at midlatitudes of the Northern Hemisphere. Data are obtained from measurements carried out on aircrafts (circles), on ships (squares), and at different land based stations during clean air conditions (triangles). The figure includes data (dots) measured by Rowland and colleagues (see Blake 1984) at similar latitudes in air from the Pacific Ocean (from Bolle, Seiler, and Bolin 1985).

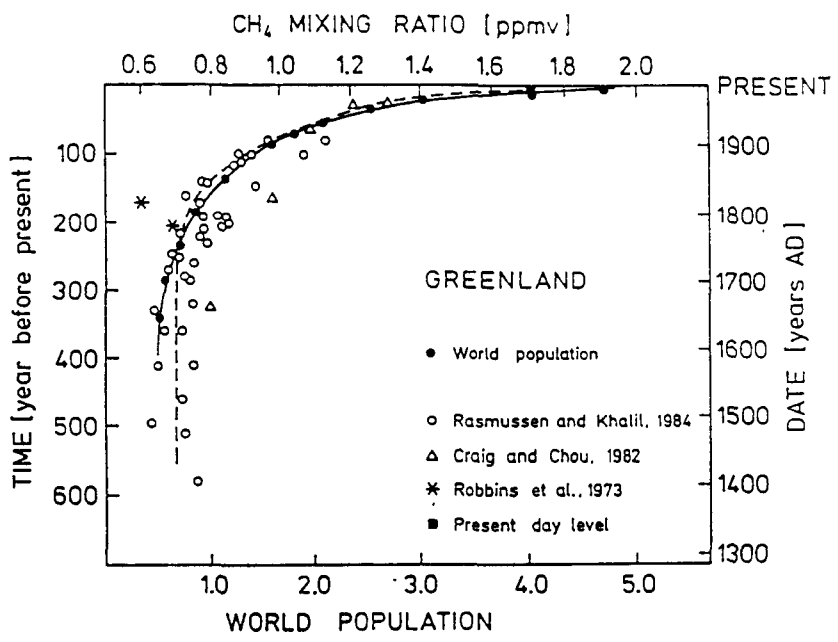


Figure 5. Growth of Human Population (in billions) and Increase of Atmospheric CH_4 Mixing Ratios (concentrations) During the Last 600 years (from Bolle, Seiler, and Bolin 1985).

Table 1. Estimated Trend of CH_4 Emission Rates from Individual Ecosystems (Tg per Year) (from Bolle, Seiler, and Bolin 1985).

Sources	1940	1950	1960	1970	1975	1980
Ruminants	53.5	58	68.5	78.5	84	86
Rice paddies	64.5	74.5	89	105	115	117
Swamps/Marshes	79	73	63	54	51	47
Other biogenic	15.5	18	20.5	23	24	25
Biomass burning	49	57	65	71	75	79
Natural gas	2	5	11	24.5	30	34.5
Coal mining	19	19	26	29	31	35
Total	283	305	343	385	410	423

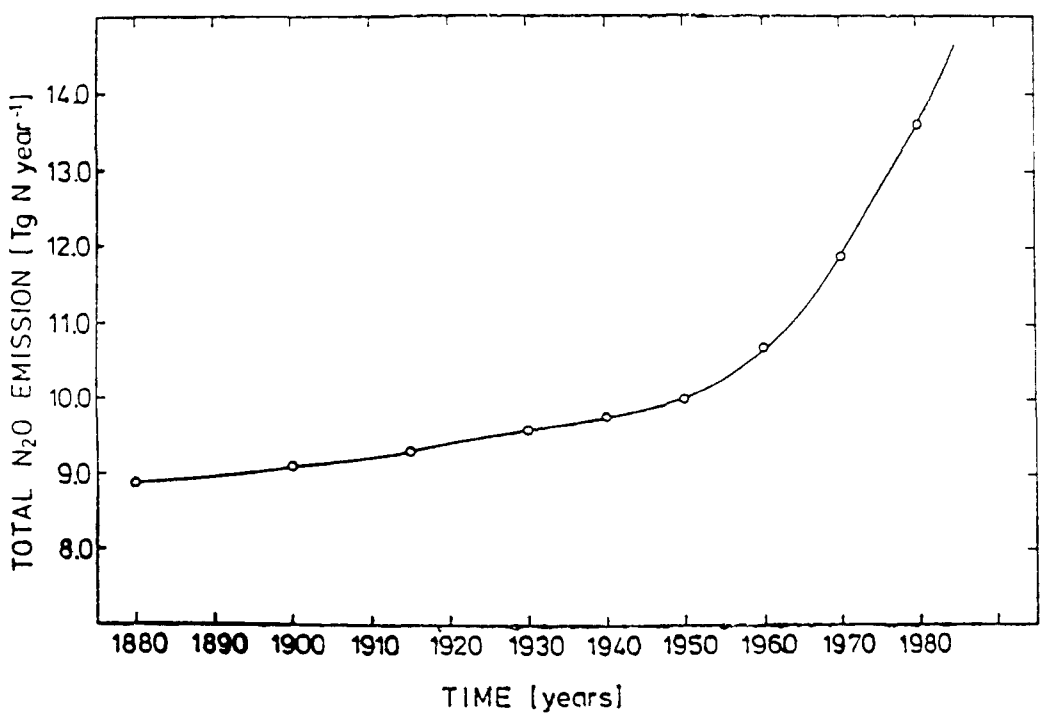


Figure 6. Trend of Estimated Total N_2O Emission Rates Between 1880 and 1980 (from Bolle, Seiler, and Bolin 1985).

"greenhouse" gas, it also reduces stratospheric ozone through chemical reactions that form nitric oxide. It is estimated that a doubling of the N_2O concentration alone would reduce stratospheric ozone by 3% to 5%.

Increases in carbon dioxide caused primarily by burning fossil fuels are well documented from the Pacific to the Atlantic, and from the North to the South Pole (see Figure 7). Projection of future CO_2 concentrations has become one of the favorite indoor sports of scientists and economists. Eighty percent of the global energy demand is currently met by burning fossil fuel. Projections of energy demand and of the mix of energy sources that will be used are uncertain. As a result, estimates of when CO_2 concentrations will double the preindustrial levels of about 275 ppm are uncertain, ranging from the middle to the end of the next century.

The chlorofluorocarbons (CFCs)-used as refrigerants, solvents, propellants for spray cans, and in other ways-are exclusively manmade. Since the mid-1970s they have been identified as a source of chlorine in the stratosphere, and thus as a threat to the ozone layer. The most important of the CFCs are $CFCl_3$ (F11) and CF_2Cl_2 (F12). Global emissions of F11 and F12 increased rapidly until the early 70s, followed by a slight decline caused by restrictions on spray can uses in North America and Scandinavia (see Figure 8). However, other uses have continued to increase and as noted, concentrations in the atmosphere of these long-lived substances grow by 5% to 7% per year (see Figure 9).

The effects of these changes on ozone in the troposphere and stratosphere have been observed. Ozone is a radiatively active gas that shields the earth from ultraviolet B (UV-B) radiation from the sun. A 1% decrease in ozone in the atmosphere results in a 2% increase in UV-B radiation, which in turn would cause a 4% increase in skin cancer. There are considerable uncertainties in trends in ozone concentrations since individual measurements at times require significant corrections and since the limited number of individual measurements for large segments of the troposphere or stratosphere may not be entirely representative. The data available, for example, from Resolute, NWT, and Hohenpeissenberg, Germany (see Figure 10), strongly suggest that an <u>increase</u> in ozone near the ground in the middle and high latitudes of the Northern Hemisphere has occurred over the past few decades because of industrial activities at a rate of 1% to 2% per year. At the same time, stratospheric ozone concentrations between 28 and 35 km above the ground appear to be declining; satellite data suggest that levels have declined as much as 5% at the 45-km (1 mb) level. Because about 90% of the atmosphere's ozone is in the stratosphere, some estimates of total column ozone indicate that small decreases have occurred since 1960.

However, the most startling change in stratospheric ozone has been observed over Antarctica. The Dobson spectrophotometer at Halley Bay (76°S) operated by British scientists has shown decreases in ozone in the Southern Hemisphere spring, especially since the early 70s, amounting to more than 40% for the month of October. Recent satellite measurements from Nimbus 7 indicate that this is a much more widespread effect than suspected and that the decline appears to extend over the whole area of the winter polar vortex. While several workers have suggested that this is caused, at least in part, by chlorine increases in the stratosphere from the chemicals discussed previously, the modeling of the mechanisms to explain such a rapid decline remains a major scientific problem.

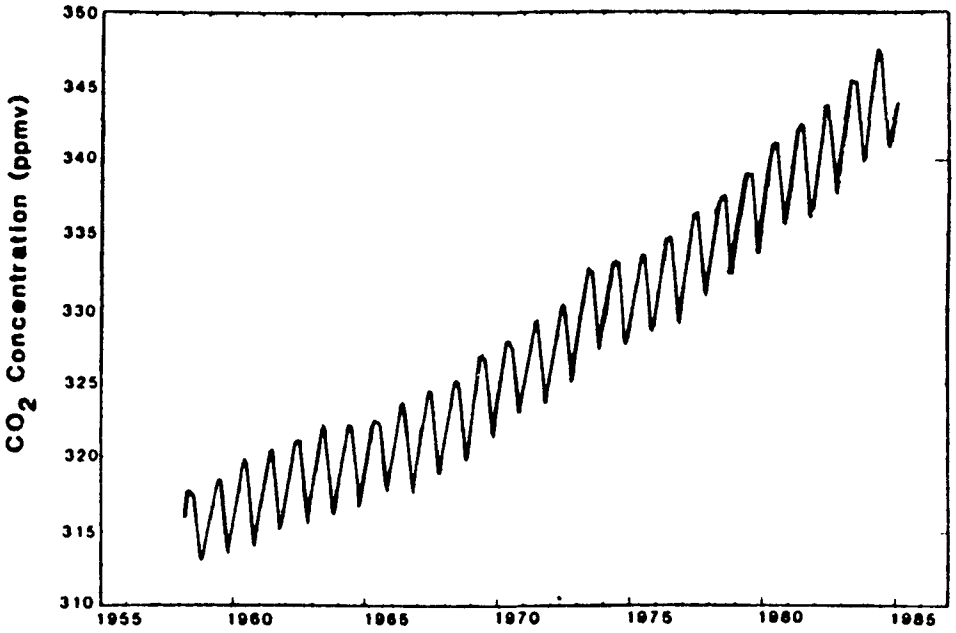


Figure 7. Carbon Dioxide Concentrations

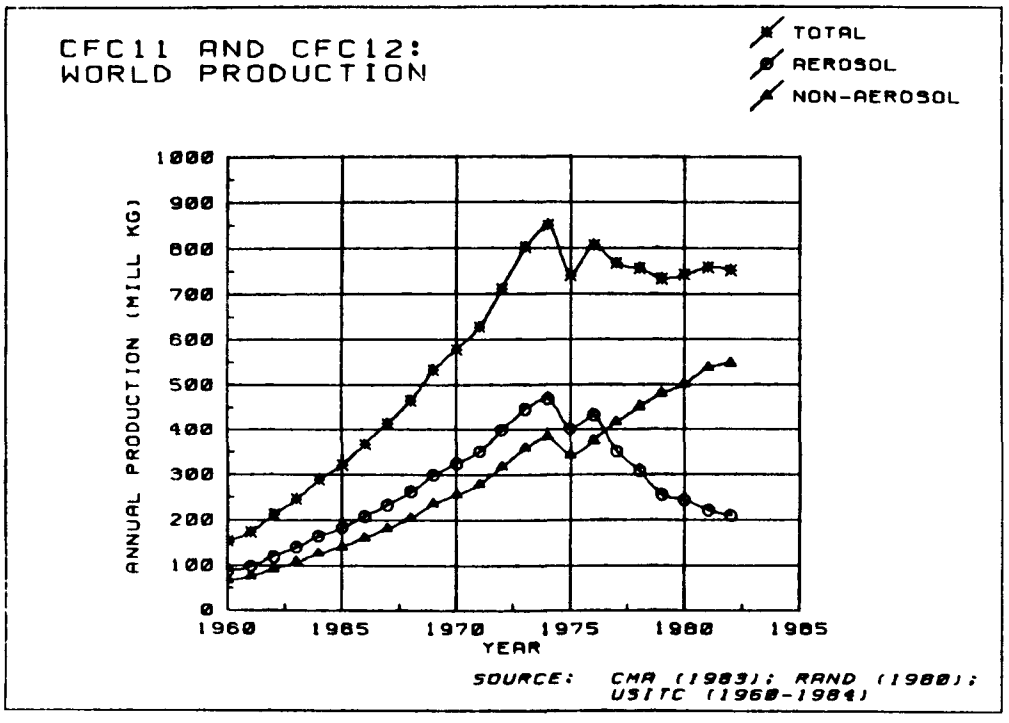


Figure 8. World production has remained nearly constant since the mid-1970s. While aerosal production has steadily declined, nonaerosol production has consistently increased.

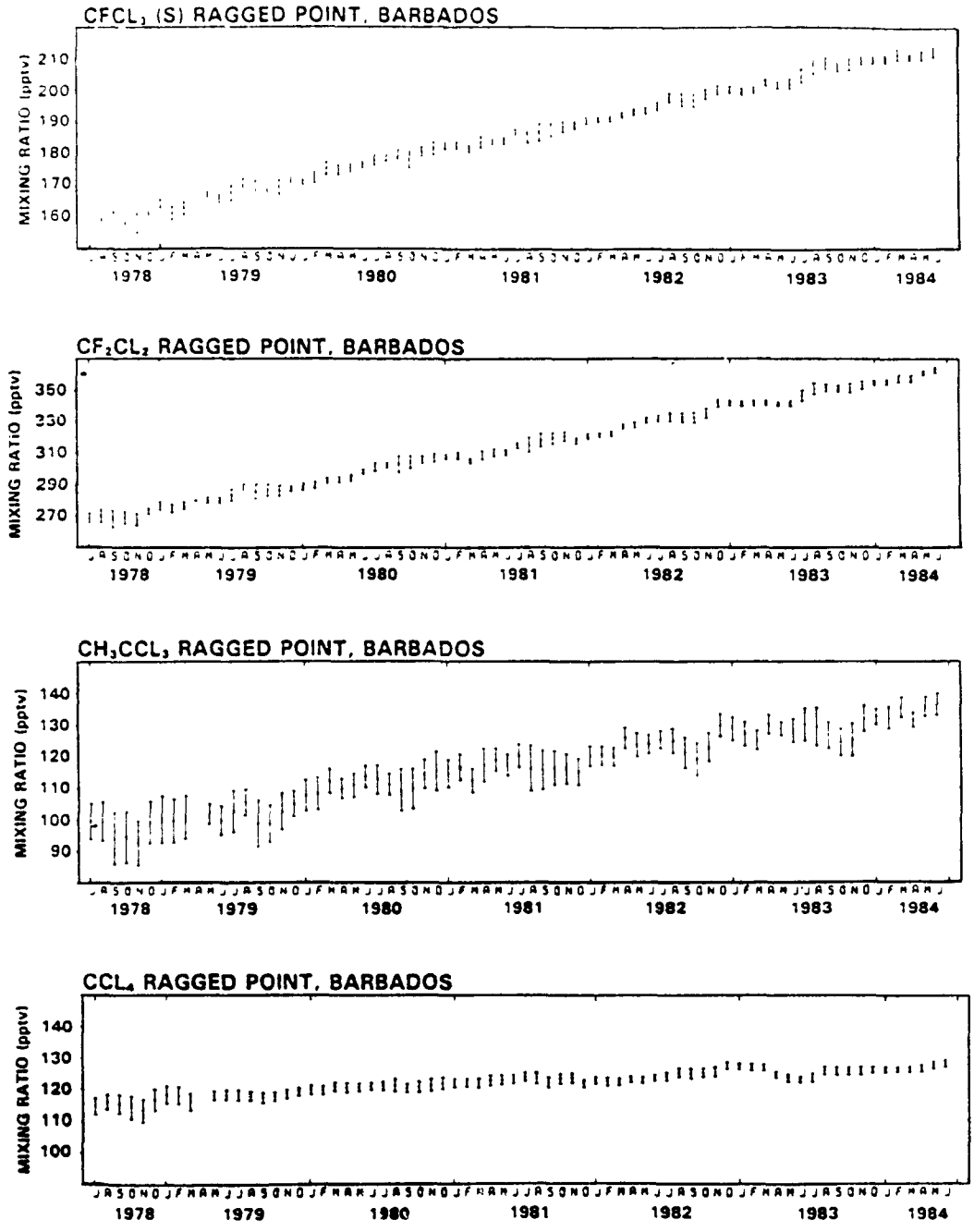


Figure 9. Monthly Mean Mixing Ratios (concentrations) and Monthly Variances of CFC-11, CFC-12, CH_3CCl_3, and CCl_4 Measured Four Times Daily on a Gas Chromatograph at the Ragged Point, Barbados ALE/GAGE Station During the First Six Years of the ALE/GAGE Network (parts per trillion volume).

Source: NASA Assessment Report

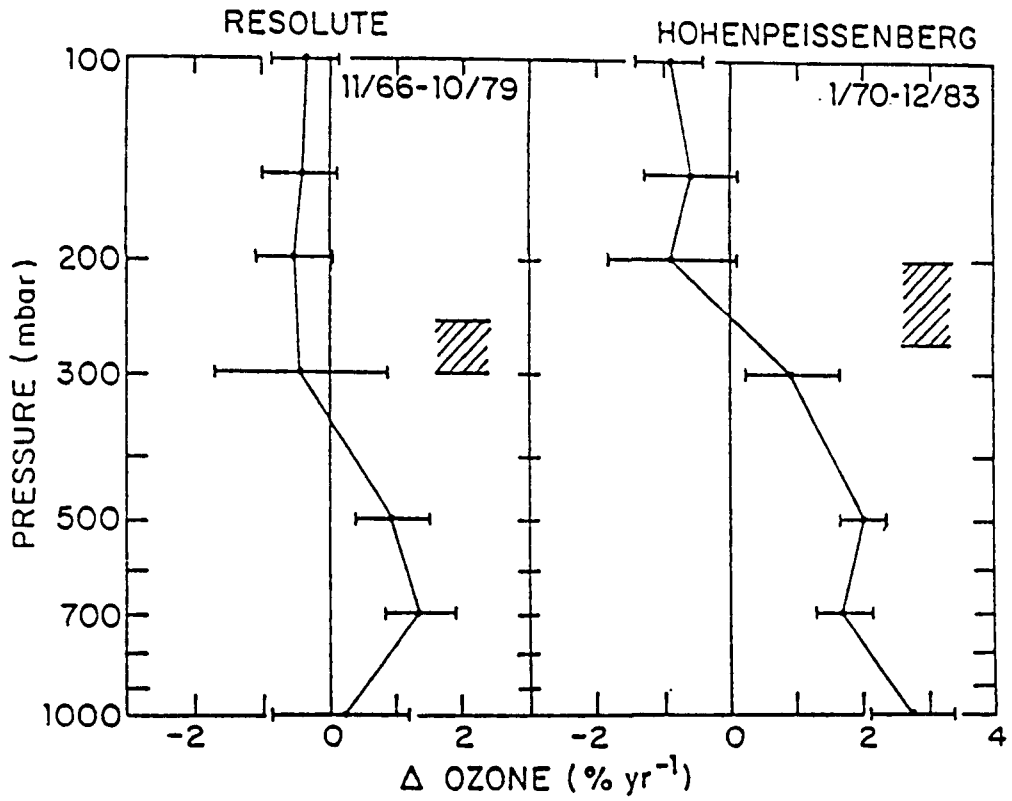


Figure 10. Percent increase or decrease in ozone at various altitudes (expressed as pressure in millibars) at Resolute (75°N, Canada, 1966-1979) and Hohenpeissenberg (47°N, Germany, 1970-1983). The horizontal bars give the 90% confidence interval. The shaded area shows the range of the tropopause heights (from Logan 1985).

Source: NASA Assessment Report

Models of ozone changes caused by these atmospheric contaminants indicate that the maintenance of stratospheric ozone is critically dependent on the rate of growth of CFC use. If CFC emissions could be returned to and maintained at the 1980 levels, the models predict only very small changes in total column ozone. Increases of 1.5% per year and 3% per year make increasingly large depletions likely. However, two-dimensional models show strong latitudinal difference with depletions throughout the stratosphere north of 40°N and some ozone increases in the lower stratosphere nearer the tropics. Polar depletions in the ozone column are predicted to be two to four times those at the equator.

The future concentrations of gases affecting the ozone layer and climate are difficult to predict since they depend on regulatory decisions by governments, energy policies and consumption, and other human interventions as well as a more thorough understanding of physical and chemical atmospheric processes. However, it is easier to predict what concentrations of some substances will be if people and governments take no action. Ramanathan and colleagues in 1985 published a comprehensive set of projections of concentrations of forty-seven trace gases of the atmosphere that affect radiation balances. Many of these have a very minor role to play. The relative importance of these gases to the "greenhouse" effect is summarized in Figure 11, which gives the cumulative equilibrium surface temperature warming caused by these gases from 1980 to 2030 as computed from a one-dimensional model following Ramanathan's work. Because of positive feedbacks predicted by general circulation models, the most probable temperature changes at the earth's surface are one and a half to two times those given in the diagram. The figure shows that CFCs are next in importance to carbon dioxide; that methane, nitrous oxide, and ozone are significant contributors; and that the forty or so other radiatively active trace gases add little to the total. Carbon dioxide is about half the story.

In October 1985 in Villach, Austria, a group of nearly 100 of the world's leading scientists and policy analysts in the field gathered to assess the present state of knowledge of greenhouse gases and climate change. The conference concluded that "The role of greenhouse gases other than CO_2 in changing the climate is already as important as that of CO_2. If present trends continue, the combined concentrations of atmospheric CO_2 and other greenhouse gases would be radiatively equivalent to a doubling of CO_2 from pre-industrial levels possibly as early as the 2030's." Hansen et al. (this volume) suggest a date as early as the 2020s.

The consensus of the results from general circulation models about the effects of such a doubling of CO_2 was also reviewed at Villach. It was concluded that the models indicate that the global mean equilibrium surface temperature would rise by 3°C ± 1.5°C. In the shorter term, a further 1°C rise beyond the 0.5°C of the past century could occur within the next two decades, making the earth's climate warmer than at any time in the past 100,000 years. However, the scientists working with these models are quick to point out imperfections of and problems with the models, particularly that the hydrologic cycle, clouds, and ocean-atmosphere interactions are not modeled with much confidence. Thus, while model results are converging on the range of values indicated, uncertainties in the modeling make many of the scientists most involved cautious about the results. They believe that we can use the

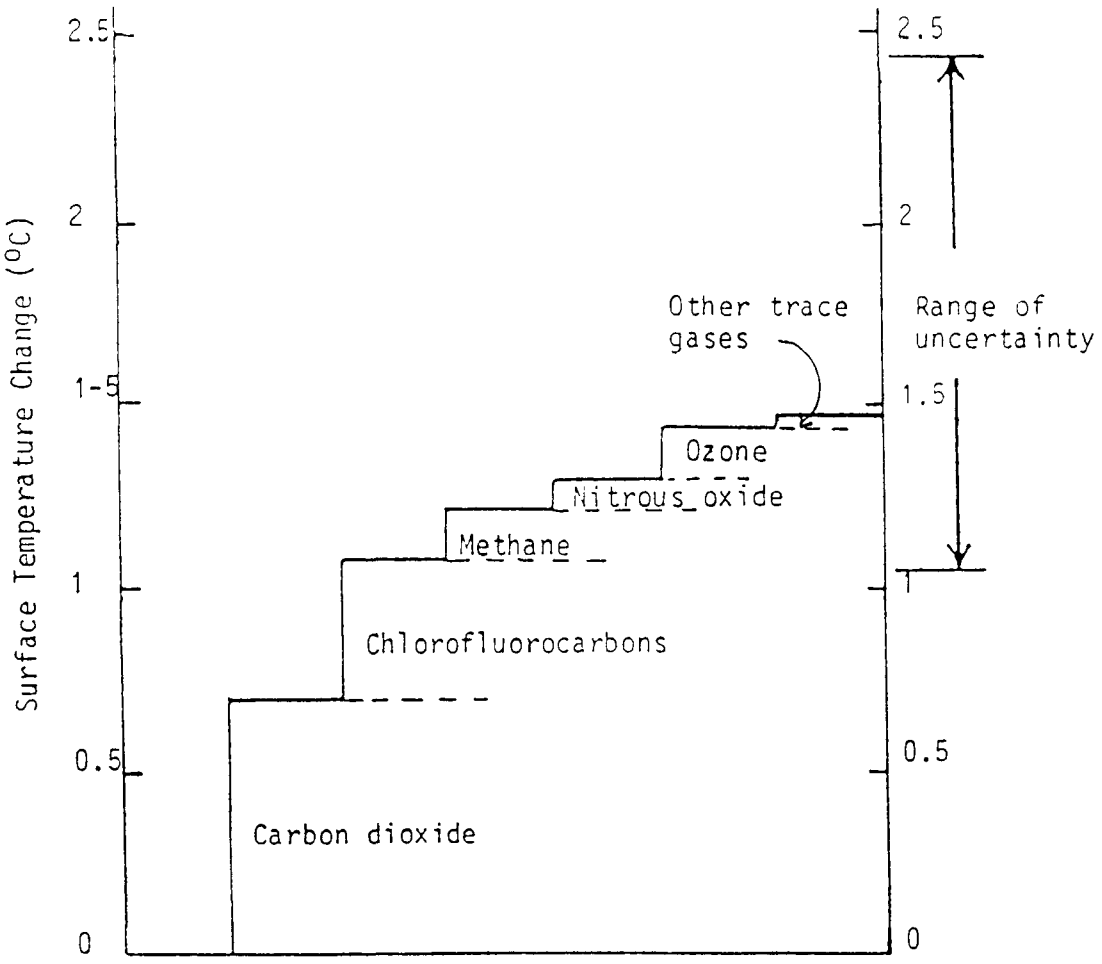


Figure 11. Cumulative Equilibrium Surface Temperature Warming Due to Increase in Carbon Dioxide and Other Trace Gases from 1980 to 2030 AD as Computed by a One-Dimensional Model (after Ramanathan et al. 1985). Due to positive feedback mechanisms as revealed by general circulation models, actual warming may be 1.5 to 2 times the values given in this figure (from Bolle, Seiler, and Bolin 1985).

outcome as some indication of what may happen, but not as a fully reliable prediction.

In addition, the models do not agree on regional distribution patterns of temperature changes or on changes in regional precipitation. The indications are, however, that the larger temperature increases will be in high latitudes in winter and autumn and that summer dryness may become more frequent in the midlatitude Northern Hemisphere (see Manabe and Wetherald, this volume). The Villach projection of sea-level rise, based simply on extrapolation of past experience, is that for global temperature increases from 1.5° to 4.5°C sea level would rise 20 to 140 centimeters (see Titus, this volume, and Thomas, Volume 3).

This has been a very brief and simplified overview of a very complex matter, i.e., the changes in the global atmosphere. It might be useful to reflect on the implications of the present state of knowledge for all of us and especially for those concerned with public policy. Four main points should be considered.

First, these are not, as some have assumed, problems for the next generation, but urgent issues for us today. The protective stratospheric ozone layer is decreasing, and preventive measures taken so far have been inadequate to arrest the global increases in the substances causing the change. Climate warming caused by greenhouse gases appears to be under way and is likely to reach very significant proportions in the first half of the next century, even if the inertia of the system caused by the oceans delays warming by a decade or two. As the Villach Conference statement says, "Many important economic and social decisions are being made today on long-term projects--in irrigation and hydro-power; combatting of drought; land use; agriculture; structural designs; coastal engineering projects; and energy planning." The statement points out that even if the consequences of global warming are ignored, the projects are based on some assumption about the climate of the next 50 to 100 years. It is a matter of real urgency to be able to provide more reliable predictions and guidance.

Second, the need is great for governments and funding agencies to support research on the changing atmospheric composition and its effects. Uncertainties in our predictions of climate change and ozone layer modification continue to be disturbing. It is especially important that major international efforts such as the World Climate Research Programme, the Global Tropospheric Chemistry Program, and the proposed International Geosphere-Biosphere Programme be adequately supported.

Third, remedial, or at least preventive, measures seem to be possible. As the Villach meeting noted, "The rate and degree of future warming could be profoundly affected by governmental policies on energy conservation, use of fossil fuels, and the emission of some greenhouse gases." I am reminded of the debate of the early 70s on how to control the rate of eutrophication of lakes. A number of nutrients were over-stimulating algal growth in many of our lakes, but one key nutrient, phosphorus, was most readily controllable. In our present case, CFCs are one group of substances that clearly have major impacts on both climate and on the ozone layer. Some of their uses for spray cans and foam blowing can hardly be considered essential and are therefore controllable. It is my view that governments should move quickly to a CFC

control protocol under the Vienna Convention on the Ozone Layer, and that individual governments and companies should be urged to limit their use of these chemicals. To advance the development of such an international control program, the directors of environmental programs from many countries need to be briefed on these issues and should discuss international remedial action. An SO_2 control protocol signed in Helsinki, July 1985, by twenty countries under the Economic Commission for Europe and ministerial meetings in Ottawa and Munich were essential steps in moving the process forward. If the scientists and bureaucrats make little progress in achieving a CFC control program by early 1987, we should ensure that the most senior elected and politically appointed officials become involved.

Finally, we must accelerate acceptance of a more comprehensive view of the earth's atmosphere and the need to protect its beneficial characteristics. The problems of the ozone layer, of greenhouse gases and climate change, of long-range transport of acidic and toxic substances are closely interrelated. They are all problems caused by human contamination of the atmosphere--the only one we have. A new approach, a new ethic, towards discharging wastes and chemical materials into the air we all breathe must soon be adopted on an international scale. Without this we will do irreparable damage to our earthly home.

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The Importance of Knowing Sooner

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ABSTRACT

Unlike most environmental problems, the greenhouse warming and ozone depletion are global in extent, possess enormous momentum for change, and may be almost irreversible once they occur. Recent scientific assessments uniformly agree that the changes that are likely to occur in this century will exceed the range of natural variation experienced in the whole last century. Given our relative ignorance of the possible effects of these changes, it would appear that the value of knowing about effects sooner is substantial.

INTRODUCTION

The relative paucity of scientific research that has been undertaken to understand the health and environmental effects of ozone depletion and global warming can, in part, be explained by the belief that has been held that these phenomena were relatively distant and uncertain. Clearly, that view is now in doubt. Recent scientific reviews sponsored by the World Meteorological Organization, the United Nations Environment Programme, and others indicate that the speed of atmospheric change has been greater than thought (NASA 1986; WMO 1986a; WMO 1986b). These reviews contend that the magnitudes of ozone depletion and global warming are likely to be large enough to emerge above the level of natural variations that have occurred within this century, which for climate, at least, has been quite large.

In this volume, papers by Hansen et al. and Stordal and Isaksen strengthen that message by presenting some important new results. Both research teams used, for the first time, the most complex models to simulate atmospheric change with realistic time-dependent scenarios of emissions. Their models predict not just global average changes in ozone and climate but the changes that will occur through time at different latitudes. The results indicate that at some latitudes, changes will be much larger than many had expected. As such, these results are certain to heighten our concern

about environmental and health effects of ozone depletion and climate change. As such, a new sense of urgency is likely to develop about the need to understand the effects of global atmospheric change.

Two other important justifications exist for understanding effects sooner. A large amount of momentum has developed for ozone depletion and global warming, and these phenomena may be essentially irreversible once they occur. Momentum is relevant because the more that exists, the harder it is to stop. Irreversibility is important because if one cannot go backwards, momentum threatens to take one forever beyond the point one wishes to go. This paper explores the forces that create momentum and irreversibility for global atmospheric systems.

MOMENTUM

Most pollution problems are local in character and can be quickly solved by reducing emissions. For example, if the concentration of particulates in a locality is judged too high, the emissions from sources that contribute to pollution in that area can be reduced proportionally to the reduction in concentrations desired. Within days of turning on the controls, the problem will be solved. The situation for global atmospheric problems is radically different.

Chlorofluorocarbons (CFCs) 11, 12, and 113; nitrous oxide; and the halons have long lifetimes (NASA 1986). Emissions of these gases do not leave the atmosphere quickly, but linger for decades or more. In fact, for CFCs 11, 12, and 113; halons 1211 and 1301; and nitrous oxide, the only real sink (loss mechanism) is the stratosphere itself, where high energy ultraviolet radiation is capable of photodissociating these gases. Consequently, for any level of emissions into the atmosphere, concentrations will increase in the lower atmosphere until the point in time that the transport to the stratosphere equals the global emissions. We are currently far from that point. Thus, if current emissions did not grow, concentrations would continue to increase for over one hundred years, as shown in Figure 1 for CFC 12. If we wanted to stabilize the concentration of CFC 12, total emissions in the world would have to be reduced approximately 85 percent immediately, as shown in Figure 2.

This disequilibrium between emissions and concentrations constitutes a kind of momentum for change in the world. Change is built into the status quo. Putting on the "brake," except in the most extreme case, would not prevent change, but would only slow it down. (Figure 3 shows the results of various reductions in emissions on the increase in 2 concentrations.

In point of fact, the world is still gathering momentum. Emissions have been increasing and are likely to continue to do so according to most studies. Figure 4 shows fifteen year projections of CFC 11 and 12 for a variety of papers presented at the UNEP conference in May. In developed nations, many uses of CFCs are growing faster than the economy--production of personal computers, in which CFC 113 is used as a solvent for the chips, is just one example. Insulation is another. In many developing nations, current consumption can be expected to grow faster than the economy, as segments of

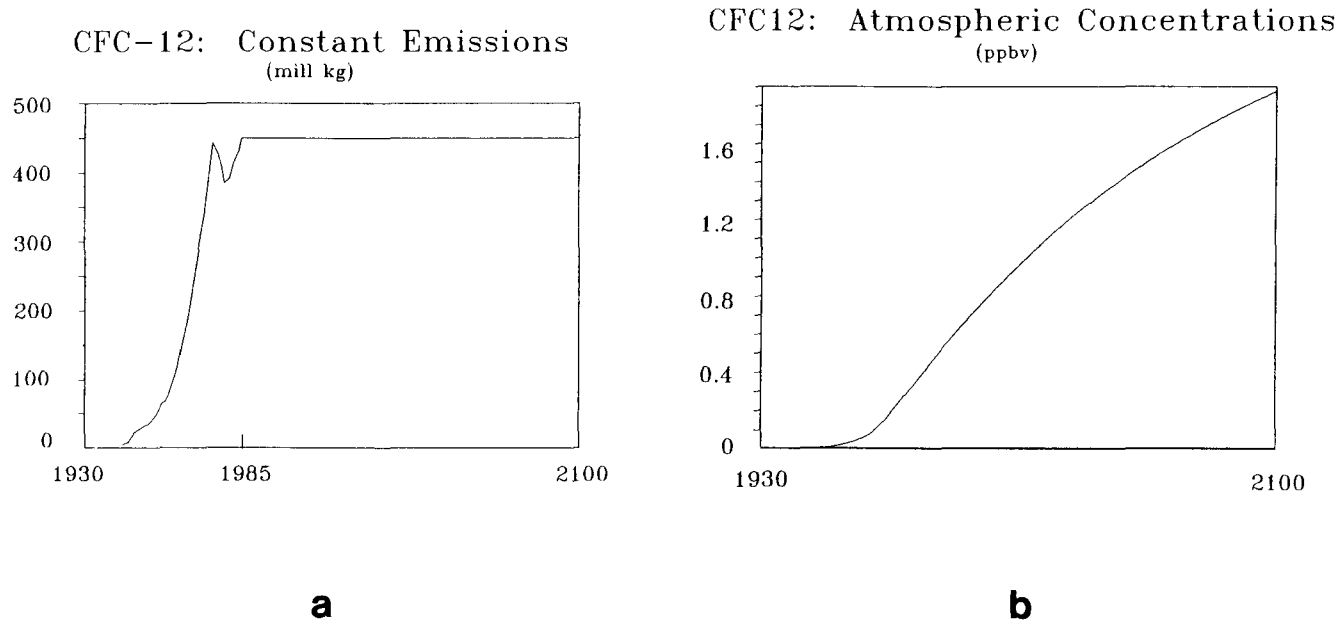

Figure 1. If future emissions of CFC-12 were held constant at today's levels (Figure 1a), atmospheric concentrations would continue to rise for over one hundred years (Figure 1b).

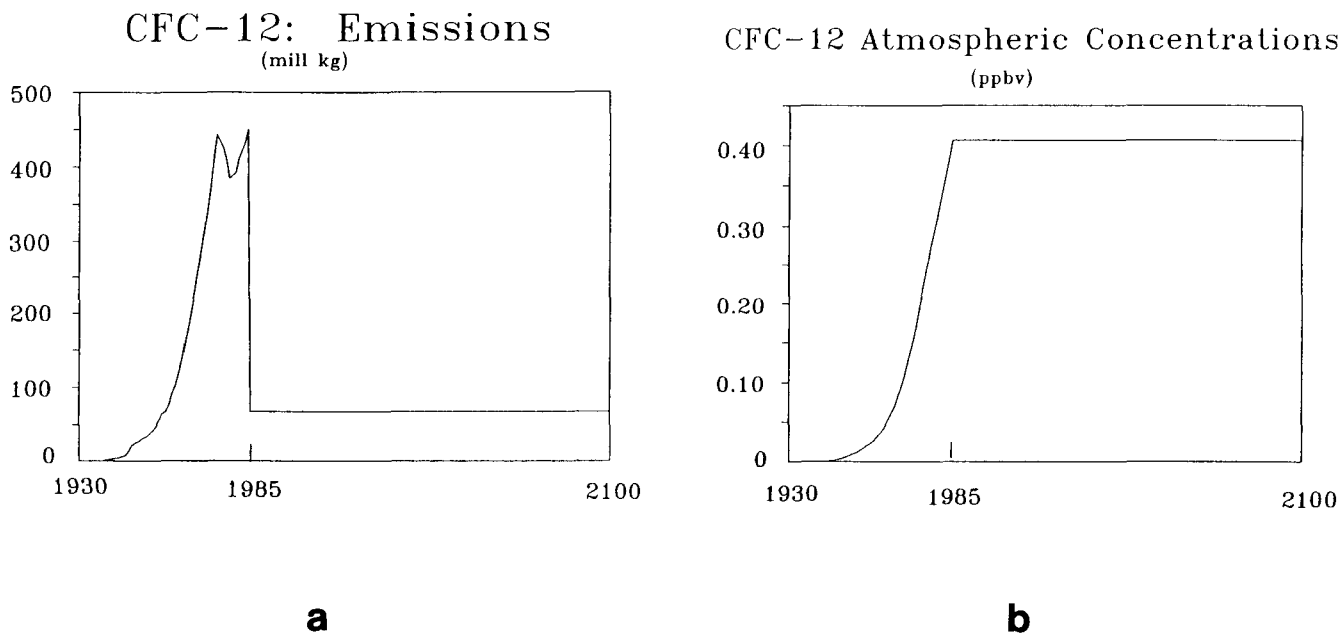

Figure 2. Atmospheric concentrations of CFC-12 are far from equilibrium. Only if emissions were cut 85% and not permitted to increase (Figure 2a) could atmospheric concentrations be held constant (Figure 2b).

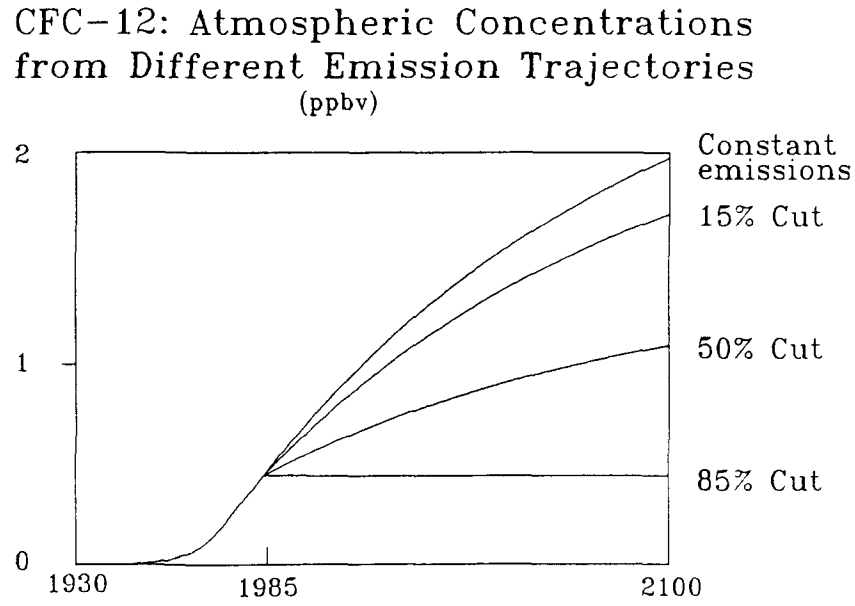

Figure 3. Atmospheric concentrations of CFC-12 will continue to rise unless emissions are cut. Holding emissions constant at today's level or even 15% or 50% lower would still allow atmospheric concentrations to grow. Only a cut of 85% or more could stablize atmospheric concentrations.

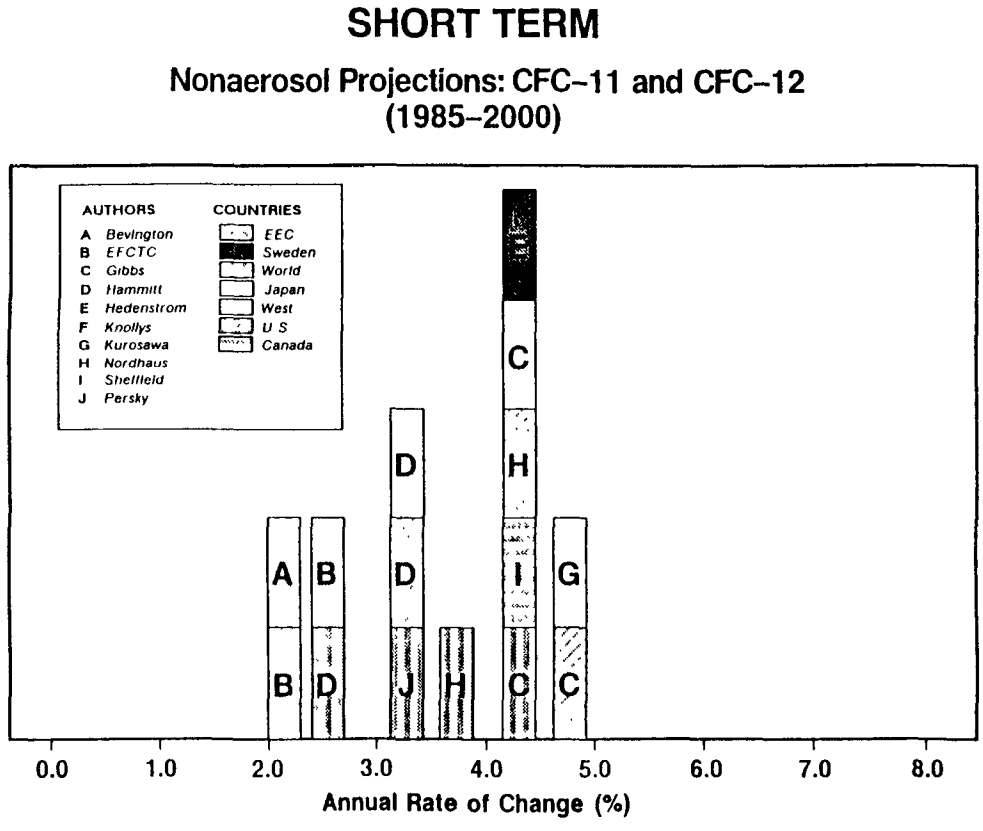

Figure 4. A variety of researchers have estimated future demand for CFCs in various countries and regions. Despite their diversity of methods and data, they are in substantial agreement that short-term demand for CFCs in non-aerosol uses will continue to increase.

the populations reach the state of being able to afford goods that use CFCs or other chemicals. People are likely to want refrigerators, air conditioning, and electronics as their wealth increases. As populations and economies grow we can expect the demand for goods and services to grow in developed nations too, including those that use potential ozone depleting chemicals. This process creates a major source of momentum for accelerated atmospheric change.

Another form of momentum exists for global warming. At the present time the earth has not experienced all the warming that would be expected from past increases in greenhouse gases. Instead, some of the infrared energy trapped by past increases in greenhouse gases has been used to heat up the upper layers of the ocean (NAS 1979). While this effect has retarded the speed of the warming to date, eventually we can expect ocean and atmosphere temperatures to rise to their equilibrium values. The current difference between the realized and equilibrium temperature constitutes a major form of momentum for global warming--a form that is inescapable. For the model simulation of global warming performed by Hansen et al. in this volume, the temperature change realized by 2000 is 1°C. The unrealized warming also turns out to be 1°C. This means that even if the concentrations of greenhouse gases were totally stabilized by that year the world would eventually experience a 2°C average global warming.

IRREVERSIBILITY

Clearly momentum makes it difficult to stop any system quickly. It is a different question whether it is possible to go back once one has stopped. As it turns out, however, restoring lost ozone or cooling the world would be difficult. As discussed earlier, the gases likely to cause these phenomena have long lifetimes. Even if emissions are totally eliminated, it could take decades for the concentrations to fall. A total elimination of emissions seems unlikely, but if it did occur in the case of ozone depletion, one would expect to eventually see the concentrations of ozone restored, all other things being equal. For global warming, this may not be the case. It may be that warming makes it impossible for all things to go back to what they were. In particular, the water vapor that has entered the atmosphere and amplified the radiative warming from other greenhouse gases may not just disappear from the atmosphere. If it resides in the atmosphere permanently, it will continue to enhance global temperature, perhaps forever. Regardless of whether this happens, the warming will last a long time.

CONCLUSION

A system that is hard to stop and that may be impossible to reverse presents a very different issue from those facing decisionmakers currently in the environmental arena. A problem that is global in nature, in which any change can expose billions of people, all ecosystems, and all outside materials to change, raises issues that are also very different from environmental problems in localized systems. It is not difficult to imagine that as recognition of the unique aspects of global atmospheric change becomes more widespread, decisionmakers will begin to focus on the effect of depletion and warming, recognizing the importance of knowing sooner.

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Our Global Environment: The Next Challenge

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The problems associated with ozone depletion, the greenhouse effect, and climate change have extraordinary ramifications for the world we inhabit. Although these problems have not yet been elevated to the same level of public awareness as toxic waste or acid rain, more and more people are becoming aware and concerned about them. The press that these issues received in the second week of June 1986 is evidence of mounting awareness and concern. There have been stories and editorials in newspapers across the country and in Canada, national television, radio, and magazines like Newsweek and The New Yorker.

On June 10 and 11, 1986 we conducted two days of hearings before the Senate Subcommittee on Environmental Pollution to explore the nature of these problems and to examine what is being done by the U.S. government, domestically and internationally, to both improve our understanding of these matters and to respond to them. Why did we decide to spend time on these problems? Why is all of this so important? Why are the policymakers demanding action before the scientists have resolved all of the questions and uncertainties? We are doing so because there is a very real possibility that society--through ignorance or indifference, or both--is irreversibly altering the ability of our atmosphere to perform basic life support functions for the planet.

This is not a matter of Chicken Little telling us the sky is falling. At our hearings, we heard graphic, powerful and disturbing testimony from distinguished scientists such as Bob Watson and Jim Hansen of NASA, Sherry Rowland, George Woodwell, Stephen Leatherman, and Carl Wunsch. The scientific evidence is telling us we have a problem, a serious problem. There is much that we know. There is a great deal that we can predict with a fair amount of certainty.

As evidenced by the October 1985 Villach Conference, there is now an international consensus among the scientific community. Although there will always be dissenters--those who claim, for example, that the earth is actually cooling, not warming--the scientific community has told us with unusual

clarity that we have a problem. We must not allow their message to fall on deaf ears.

It is true that we lack the tools to close all of the scientific gaps. We don't completely understand our climate systems and we cannot predict precise outcomes. But we will always be faced with a level of uncertainty. The current gaps in scientific knowledge may not be closed for many years. Scientists have characterized our treatment of the greenhouse effect as a global experiment. It strikes me as a form of planetary Russian roulette.

We should not be experimenting with the earth's life support systems until we know that when the experiment is concluded, the results will be benign. As Russell Peterson (former Chairman of the President's Council on Environmental Quality) who worked as a chemist for twenty-six years has said, "We cannot afford to give chemicals the same constitutional rights that we enjoy under the law ... chemicals are not innocent until proven guilty."

By not making policy choices today, by sticking to a "wait and see" approach, we may in fact be making a passive choice. By allowing the so-called "greenhouse" gases to continue to build up in the atmosphere, this generation may be committing all of us to severe economic and environmental disruption without ever having decided that the value of "business as usual" is worth the risks.

Those who believe that these are problems to be left to future generations are misleading themselves. Human activities to date may have already committed us to some level of temperature change. If historical evidence is any guide, a slight warming may be enough to turn productive, temperate climates into deserts. To quote from a recent Department of Energy report, "large changes in both precipitation and the extent of deserts and grasslands can be associated with relatively small variations in the global mean temperature."

The path that society is following today is much like driving a car towards the edge of a cliff. We have a choice. We can go ahead, take no action and drive off the edge--figuring that, since the car will not hit the bottom of the canyon until our generation is already long gone, the problem of coping with what we have made inevitable is a problem for future generations. We can hope that they will learn how to adapt. On the other hand, we can put the brakes on now, before the car gets any closer to the edge of the cliff and before we reach a point where momentum will take us over the edge.

What do we do about all of this?

First, it is important to focus attention on the potential effects of ozone modification and climate change. Simply telling people that there will be a change is not enough. They need to understand how they will be affected by it. The International Conference on the Effects of Ozone Modification and Climate Change was an excellent step in that direction. Many people came a long way to participate in that gathering.

In addition, we must begin to consider the choices that will have to be made if we are going to avoid further build-up of harmful gases in the atmosphere. All of us must recognize that these are no longer just science issues. They are not policy issues. They demand solutions.

Many of the government witnesses who appeared before my Subcommittee argued that we need more studies. They contend that there are too many scientific uncertainties to warrant action. Only EPA Administrator Lee Thomas recognized what is at stake here. He was the only decisionmaker from the government who appreciated the fact that there will always be scientific uncertainty and that policymakers and those who make regulatory decisions cannot allow themselves to be paralyzed by these gaps in knowledge.

Sure, we can continue to study the problem--and we should continue our studies--but we cannot wait until these studies are completed. We need action.

Those who argue against action like to recite the caveats, uncertainties, and margins of error that accompany scientific reports and projections in this area. For those people, it is worth noting that the margins of error usually associated with the greenhouse effect are in terms of decades. The issues of magnitude and timing need to be resolved but they do not need to be resolved before we take action. It is important to talk about projections of, for example, global warming over the next 50 to 100 years. But disagreements over the accuracy of projections for that time frame obscure the issue: Do we have the right to pollute the atmosphere today in a manner that will wreak havoc in as few as 100 to 300 years?

Obviously, no single step is going to solve the multitude of problems associated with these matters. But we must not let the enormity of the task keep us from taking a series of small steps.

The growing use of chlorofluorocarbons (CFCs) is a prime candidate for controls. Given the risks associated with ozone modification and climate change, a treaty that limits the availability of CFCs would seem to be a sensible course to pursue. The good news is that, under the leadership of the United Nations Environment Programme, negotiations aimed at developing an international agreement to limit future growth in CFCs--to impose controls--are currently underway. The not-so-good news is that we don't have an agreement yet.

At the Environmental Pollution Subcommittee hearings, Dr. Rowland raised an interesting suggestion that I intend to examine more closely: In addition to imposing controls on the use of CFCs generally, why don't we redesign equipment such as car air-conditioners to use alternative, less harmful forms of CFCs? Although CFCs are not the only source of the problem, they are a significant factor and controlling them would represent a major accomplishment.

The need for international cooperation in addressing these matters is obvious. We are dealing with a global issue. But the difficulty of getting international agreement should not keep the United States from taking action unilaterally. By taking such action, we can move once again into the role we once proudly held: we can be world leader in environmental protection. We

can set the example. A country as large and as powerful as the United States can afford to make temporary sacrifices that ultimately will benefit all of mankind.

The importance of these issues is matched only by the complexity of them. But we have created complex problems before and we have responded to them with creative solutions. There is no reason to believe that the only answer is to throw up our hands and wait for the inevitable.

We lose so very little by trying. We lose everything by doing nothing.

Tough choices need to be made and we should start what promises to be a long, sometimes frustrating process of making policy choices and regulatory decisions. All of us will have key roles to play in that process. By working together, we can attempt to minimize the disruptions that go along with changes in the status quo. But there will be changes. Present and future generations of all life forms depend on our making the right choices.

The Greenhouse Effect

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I am pleased to have the opportunity to join the other authors of this report to accelerate our progress on the global problems of climate change. In order to resolve these issues, we will need the kind of international cooperation and leadership that organizations like the United Nations Environment Programme and the U.S. Environmental Protection Agency can provide. Let me briefly discuss one of our gravest climatic concerns--and perhaps the most significant environmental problem of the next century--the greenhouse effect.

The buildup of atmospheric carbon dioxide and other trace gases is causing a global warming that could have disastrous results on sea level, agriculture, and the climate in general. Other papers present some of the forecasts--a 3 to 8 degree (F) temperature increase by 2030, a 10 percent decrease in crop yields, more frequent tropical storms. And if today's worst case scenarios come true we may have only a few decades left in which to decrease these impacts.

My interest in the greenhouse effect goes back several years, and I have chaired three congressional hearings on the phenomenon. During the first hearing in 1981, a number of prominent scientists, including Professor Roger Revelle of the University of California, testified that the greenhouse effect was not a hypothesis but a reality. This marked perhaps the first time that the scientific community had reached a consensus on this point.

The evidence to substantiate that conclusion was not long in coming. In 1982, Dr. James Hansen of NASA and Professor George Kukla of Columbia University testified that the rise in carbon dioxide levels could be correlated very closely with a rise in the earth's mean temperature, a shrinking of glacial ice, and the resulting rise in the earth's mean sea level. At that time the Washington Post, in an editorial, stated that the greenhouse effect was no longer just something for the "sandals and granola" crowd; it was in the mainstream of scientific thought.

The most comprehensive evaluations of the greenhouse effect were presented at the third hearing in 1984. One was an EPA report predicting a global temperature increase of 3.6 degrees Fahrenheit by the year 2040, and a rise of as much as 9 degrees Fahrenheit by the year 2100. This would result in sea level increases ranging from 4.5 to 7 feet by the end of the next century.

A 1983 report from the National Academy of Sciences was more conservative in its projections. The NAS predicted a 2 to 8 degree Fahrenheit rise in temperature along with a "modest" 2.5 foot rise in the sea levels by the year 2100. The major difference between the two studies was that EPA included the impact of all the greenhouse gases, including CFCs and methane, as well as carbon dioxide. The Academy projections were based solely on increased carbon dioxide concentrations.

In October 1985, a conference on the greenhouse effect brought scientists from twenty-nine countries to Villach, Austria. These scientists concluded that "...greenhouse gases are likely to be the most important cause of climate change over the next century." They went on to recommend that governments should "...take into account the results of this assessment in their policies on social and economic development, environmental programs, and control of emissions of radiatively active gases."

We must explore measures to prevent and mitigate the impact of the greenhouse effect. If there is to be an effective global effort to address this major environmental problem, then all nations must coordinate their activities.

To address this issue, I have introduced Senate Concurrent Resolution 96. The bill calls for an International Year on the Greenhouse Effect and would be the beginning of a long-term cooperative effort by scientists from all over the world.

The legislation would coordinate and promote domestic and international research efforts on both the scientific and policy aspects of this problem, identify strategies to reduce the increase of carbon dioxide and trace gases, investigate ways to minimize the impact of the greenhouse effect, and establish long-term research plans.

The concept of an international year of study has been used successfully in the past. In fact, the best and most complete collection of data based on atmospheric concentrations of carbon dioxide began in 1957 as a result of the International Geophysical Year. At that time a sampling station was established on Mona Loa, Hawaii. Today scientists are still collecting data from that station.

I believe this legislation will markedly improve national and international research efforts. In time, it will produce the vital data that the United States and other nations need to establish a long-term workable corrective policy.

Paul Brodeur pointed out in the June 9, 1986 issue of the New Yorker that we have known about the greenhouse effect and ozone depletion for over a decade, yet our efforts to develop corrective solutions have been minimal. He

quotes Professor Sherwood Rowland of the University of California at Irvine who discovered the impact of chlorofluorocarbons on the ozone layer, "...what's the use of having developed a science well enough to make predictions, if in the end all we're willing to do is stand around and wait for them to come true?"

The greenhouse effect is complicated and worrisome, and seems too overwhelming to resolve. But its potential impact is far too disastrous to ignore. The longer we wait, the worse the impact will be because the effect of the greenhouse gases is cumulative. If we wait much longer to act, it may be too late.

OZONE MODIFICATION AND SUMMARY OF UV-B EFFECTS

Atmospheric Ozone

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INTRODUCTION

For several decades scientists have sought to understand the complex interplay among the chemical, radiative, and dynamical processes that govern the structure of the earth's atmosphere. During the last decade or so there has been particular interest in studying the processes that control atmospheric ozone, since it has been predicted that human activities might cause harmful effects to the environment by modifying the total column amount and vertical distribution of atmospheric ozone. Most of the ozone in the earth's atmosphere resides in a region of the atmosphere known as the stratosphere. The stratosphere extends from about 8 km at the poles and 17 km at the equator, to about 50 km above the earth's surface. Ozone is the only gas in the atmosphere that prevents harmful solar ultraviolet radiation from reaching the surface of the earth. The total amount of ozone in the atmosphere would, if compressed to the pressure at the earth's surface, be a layer about one-eighth of an inch thick. Figure 1 schematically illustrates the vertical distribution of ozone and temperature. Unlike some other more localized environmental issues (e.g., acid deposition) ozone layer modification is a global phenomenon that affects the well-being of every country in the world. Changes in the total column amount of atmospheric ozone would modify the amount of biologically harmful ultraviolet radiation penetrating to the earth's surface, resulting in potential adverse effects on human health (skin cancer and suppression of the immune response system) and on aquatic and terrestrial ecosystems. Changes in the vertical distribution of atmospheric ozone, along with changes in the atmospheric concentrations of other infrared-active (greenhouse) gases, could contribute to a change in climate on a regional and global scale by modifying the atmospheric temperature structure, which could lead to changes in atmospheric circulation, in precipitation patterns, and in sea level. (See Hansen et al; Titus; and Manabe and Witherald, all in this volume, for discussion of the greenhouse effect and consequences of global warming.)

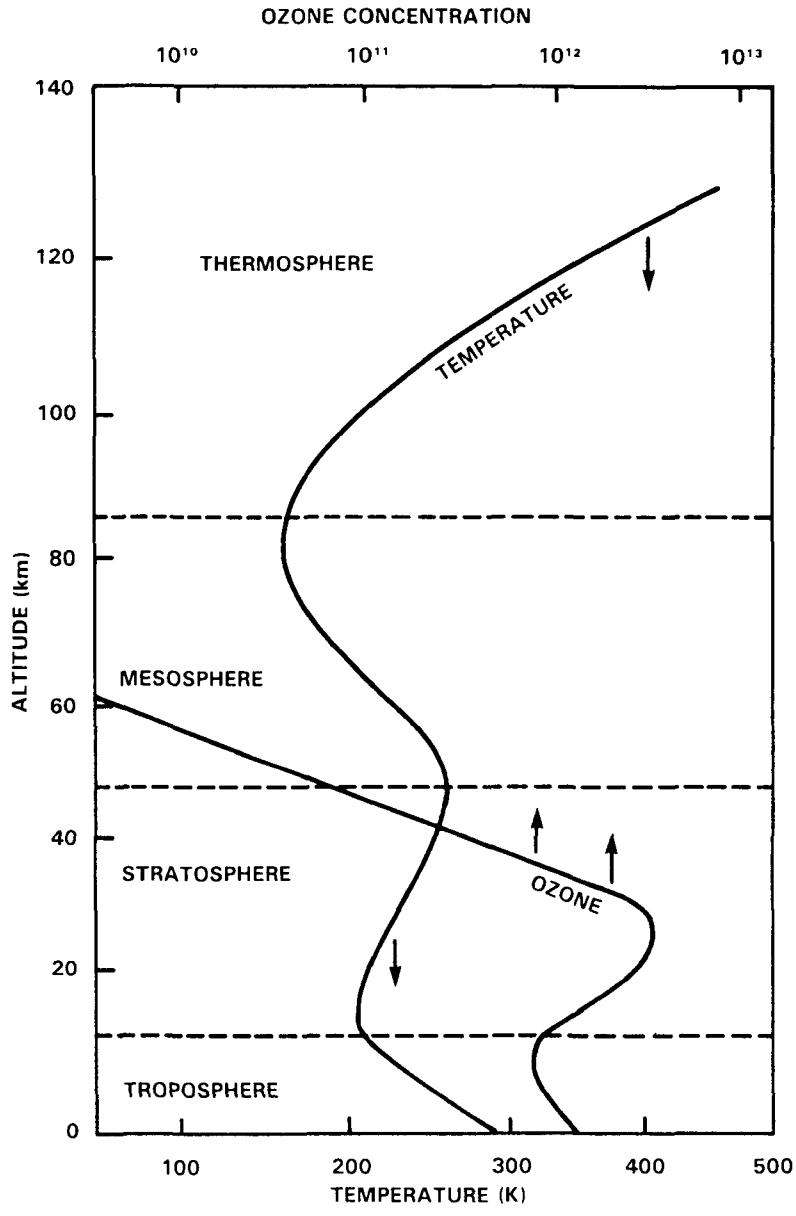

Figure 1. Temperature Profile and Distribution of Ozone (molecules per cubic centimeter) in the Atmosphere

The ozone issue and the greenhouse warming issue are strongly coupled because ozone itself is a greenhouse gas, and because the same gases that are predicted to modify ozone are also predicted to produce a climatic warming. These gases include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several chlorofluorocarbons (CFCs), including chlorofluorocarbons 11 ($CFCl_3$) and 12 (CF_2Cl_2), and are precursors to the hydrogen, nitrogen, and chlorine oxides, which can catalyze the destruction of ozone in the stratosphere by a series of chemical reactions. Concentrations of these gases in the parts per billion range control the abundance of ozone whose concentration is in the parts per million range. (For example, one molecule of a chlorofluorocarbon destroys thousands of molecules of ozone.) CO and CO_2 can affect ozone indirectly. CO controls the concentration of the hydroxyl radical (OH) in the troposphere, which itself controls the atmospheric concentrations of some of the gases that can affect stratospheric chemistry. CO_2 plays a key role in controlling the temperature structure of the stratosphere, which is itself important in controlling the rates at which the hydrogen, nitrogen, and chlorine oxides destroy ozone.

TRENDS IN THE CHEMICAL COMPOSITION OF ATMOSPHERE

There is now compelling observational evidence that the chemical composition of the atmosphere is changing at a rapid rate and on a global scale. The atmospheric concentrations of CO_2, CH_4, N_2O, and CFCs 11 and 12 are currently increasing at rates ranging from 0.2% to 5.0% per year (Figure 2 shows the trends for four chlorinated gases, and Figure 3 shows the global trend for methane). The concentrations of other gases important in the ozone depletion and global warming issues are also increasing, some at an even faster rate. These changes in atmospheric composition reflect in part the metabolism of the biosphere and in part a broad range of human activities, including agricultural and combustion practices. It should be noted that the only known source of CFCs is industrial production. CFCs are used for a variety of applications, including aerosol propellants, refrigerants, foam blowing agents, and solvents. At present one of our greatest difficulties in accurately predicting future changes in ozone concentrations or global climate is our inability to predict the future evolution of the atmospheric concentrations of these gases. We need to understand the role of the biosphere, and the impact of human activities upon it, in regulating the emissions to the atmosphere of gases such as CH_4, CO_2, N_2O, and methyl chloride (CH_3Cl) and we need to know the most probable future industrial release rates of gases such as the CFCs, N_2O, CO, and CO_2, which depend upon economic, social, and political factors.

One important aspect of the ozone and global warming issues is that the atmospheric lifetimes of gases such as N_2O, $CFCl_3$, and CF_2Cl_2 are known to be very long. Consequently, if there is a change in atmospheric ozone or climate caused by increasing atmospheric concentrations of these gases, the full recovery of the system will take decades or centuries after the emission of these gases into the atmosphere is terminated.

THEORETICAL PREDICTIONS OF OZONE MODIFICATION

Numerical models are used as tools to predict to what extent human activities will modify atmospheric ozone and climate. The types of models

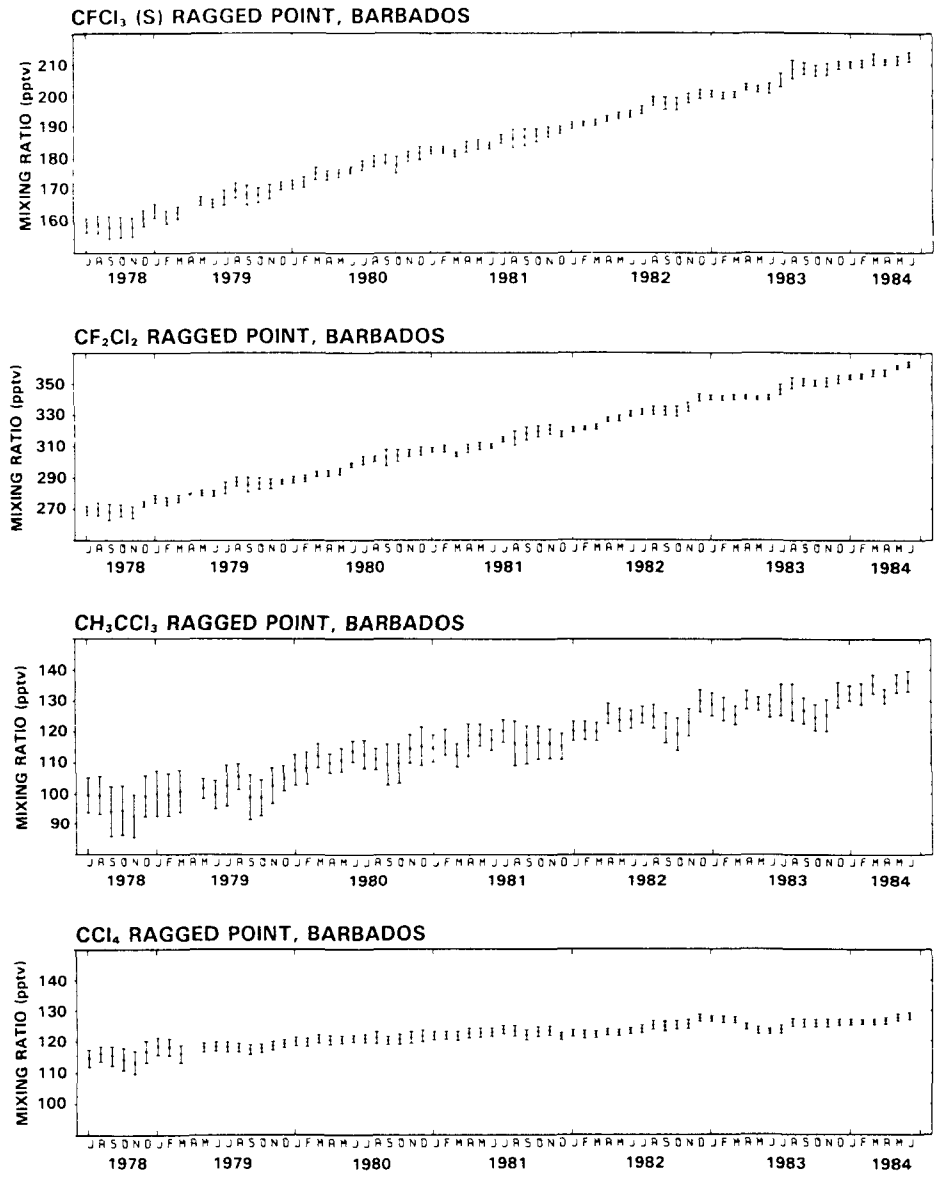

Figure 2. Monthly-mean mixing ratios and monthly variances of CFC-11, CFC-12, CH_3CCl_3 and CCl_4 measured 4-times-daily on a gas chromatograph at the Ragged Point, Barbados ALE/GAGE station during the first six years of the ALE/GAGE network.

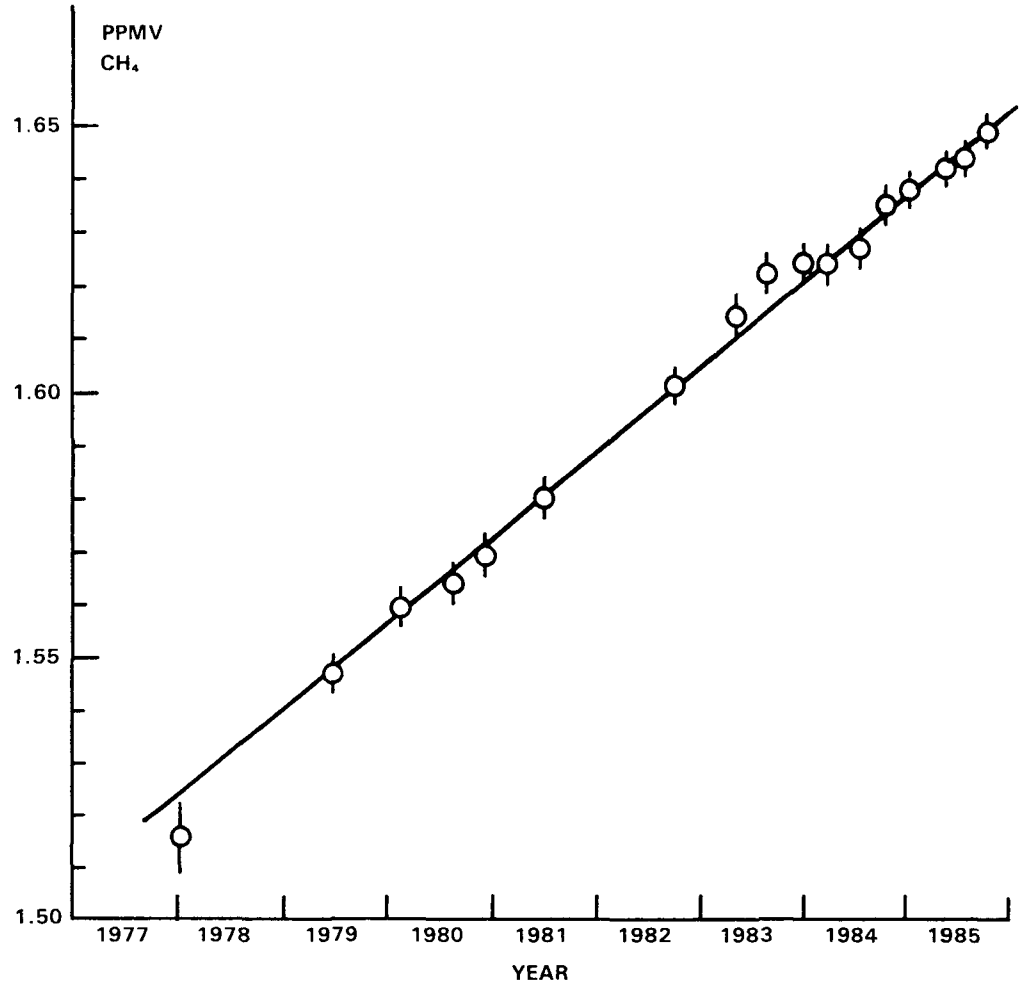

Figure 3. Globally averaged concentrations of CH_4 from 1977 to 1985.

most commonly used to predict ozone modification are known as one- and two-dimensional photochemical models. One-dimensional models predict changes in the column content and vertical distribution of ozone, but cannot predict variations in ozone modification with latitude, longitude, or season. Major progress has been made over the past few years to develop two-dimensional models which can predict the variation of ozone change as a function of season and latitude.

Three-dimensional models which include longitudinal variations are being developed to study the coupling between the chemical, radiative, and dynamical processes that control the distribution of ozone, but these models are not yet ready to perform perturbation calculations.

Because it is now well recognized that the chemical effects of these gases on atmospheric ozone are strongly coupled and should not be considered in isolation, the most realistic calculations of ozone change take into account the impact of simultaneous changes in the atmospheric concentrations of CO_2, CH_4, N_2O, the CFCs, and possibly other gases, such as CO, oxides of nitrogen (NO_x), and bromine-containing substances. The effects of these trace gases on ozone are not simply additive. Increased atmospheric concentrations of CFCs and N_2O are predicted to decrease the column content of ozone, whereas increased atmospheric concentrations of CO_2 and CH_4 are predicted to increase the column content of ozone. Therefore, it can be seen that the effects of increasing concentrations of CFCs and N_2O are to some degree offset by increasing concentrations of CO_2 and CH_4 as shown in Figure 4. This is in contrast to the global warming issue where increased atmospheric concentrations of the same trace gases are all predicted to increase the temperature of the atmosphere in an approximately cumulative manner (see Figure 7).

One-dimensional model calculations have been performed to predict how ozone would change with time (assuming that the atmospheric concentrations of CO_2, CH_4, and N_2O continue to increase at their current rates of 0.5%, 1.0%, and 0.2% per year, respectively, for the next 100 years) in conjunction with three different assumptions for annual increase rates in the emission of CFCs 11 and 12 to the atmosphere (i.e., 0.0%, 1.5%, and 3.0%). For CFC emission increases of up to 1.5% per year, the ozone column changes were calculated to be less that 3% over the next 70 years. With a CFC growth rate of 3.0% per year, the predicted ozone depletion is 10% for the next 70 years and rapidly increasing thereafter (see Figure 5). The results of these calculations demonstrate the strong chemical coupling between these gases and the time scale on which ozone changes are predicted to occur. In essence, when the growth rates of the CFCs are less than the growth rates of CH_4 and CO_2 only small column ozone changes are predicted because the CFC efffects on ozone are temporarily masked. However, when the growth rates of the CFCs exceed those of CH_4 and CO_2, these gases can no longer offset the impact of the CFCs--and large ozone depletions are predicted.

Even when the predicted column ozone changes are small, and hence little change is expected in the amount of ultraviolet radiation reaching the earth's surface, major changes in the vertical distribution of ozone are still predicted, which may have potential consequences for climate. Figure 6 shows that ozone is predicted to decrease in the middle to upper stratosphere--

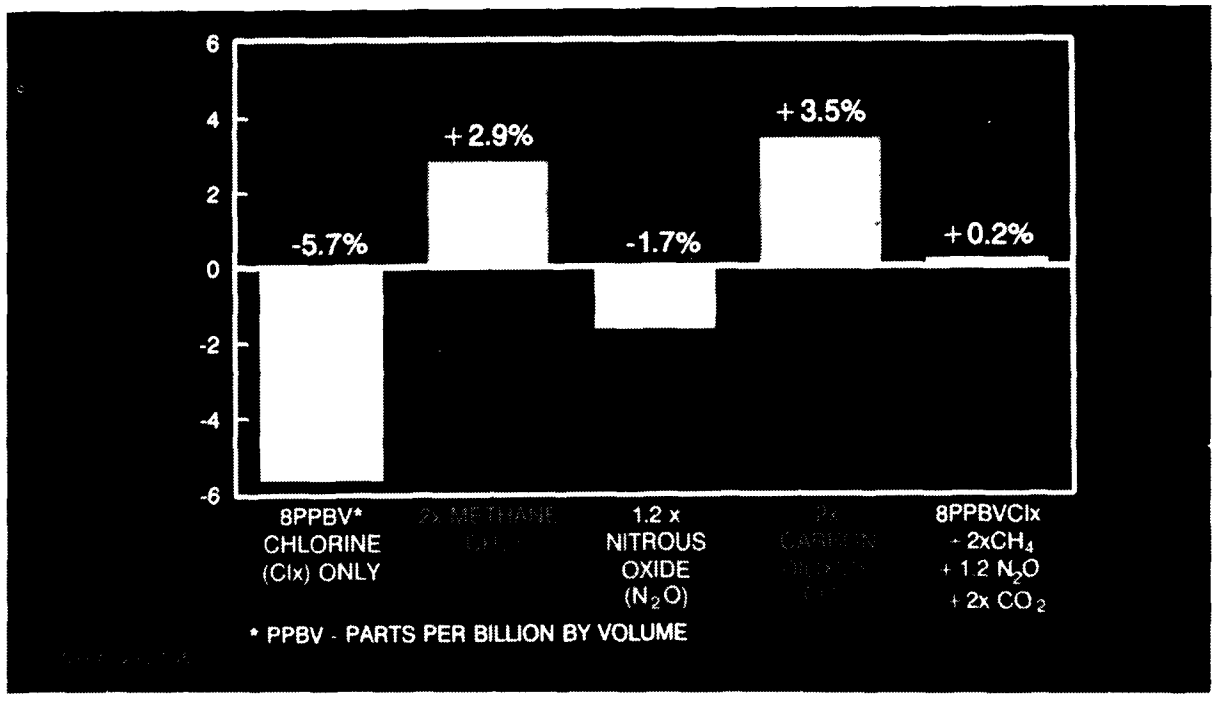

Figure 4. Ozone depletion for particular changes in atmospheric concentrations, as estimated by the Lawrence Livermore model.

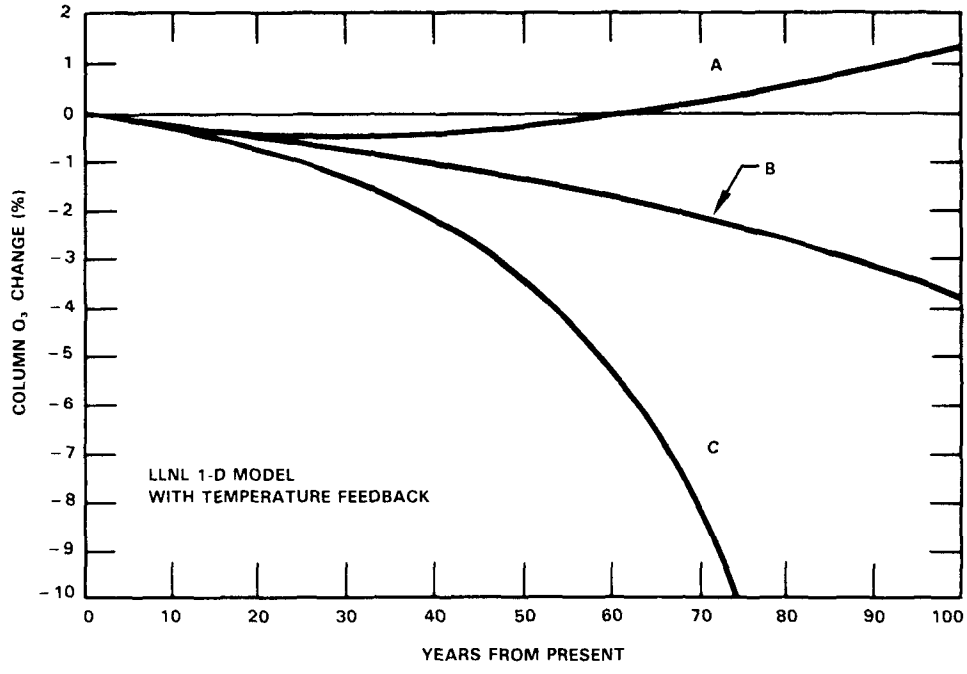

Figure 5. Calculated changes in ozone column with time for time-dependent scenarios: A (CFC flux continues at 1980 level, CH_4 increased 1% per yr, N_2O increases 0.25% per yr, and CO_2 increases according to the DOE scenario); B (CFC emissions begin at 1980 rates and increase at 1.5% per yr, other trace gases change as with A); C (same as B except CFC emissions increase at 3% per yr).

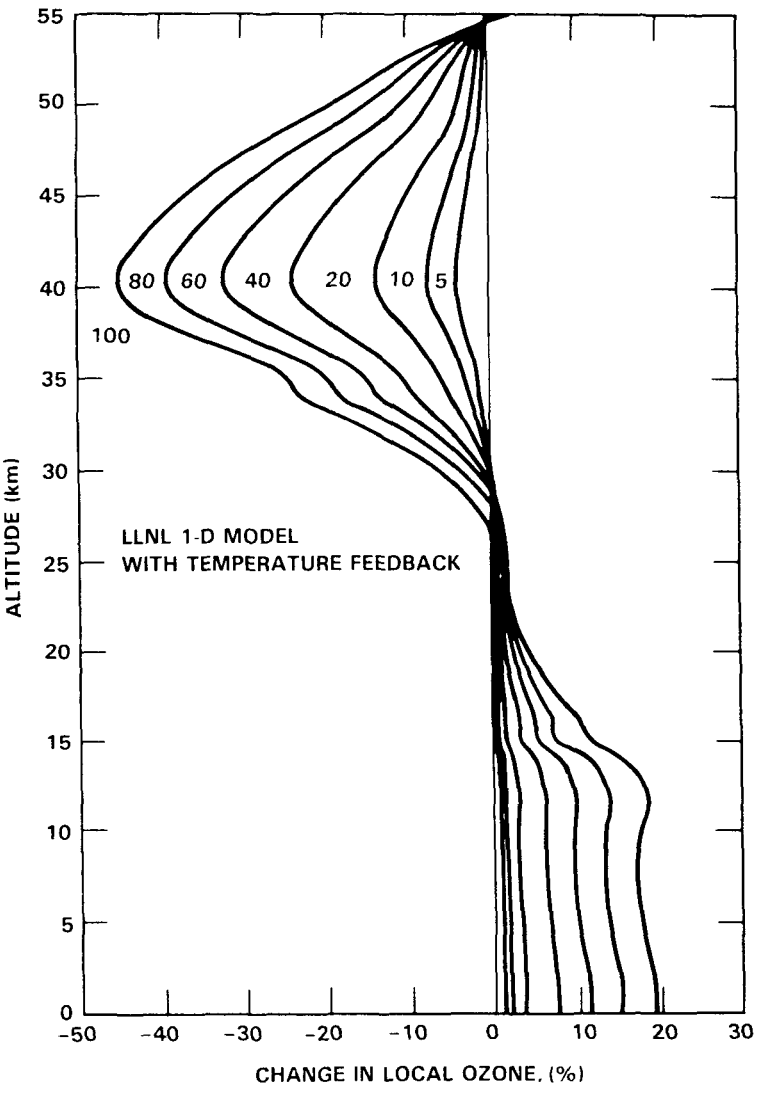

Figure 6. Calculated percentage change in local ozone at selected times 5 to 100 years in the future (scenario B of Figure 5).

primarily because of increasing concentrations of CFCs--and to increase in the troposphere primarily because of increasing concentrations of CH_4.

Two-dimensional models predict a significant variation in the ozone column, with the greatest depletions occuring at high latitudes. Depending upon the exact trace-gas scenario used to predict ozone change, the pole-to-equator ratio of ozone depletion can range from a factor of two to ten. Seasonal effects are predicted but are somewhat less pronounced than the latitudinal effects. For a given trace-gas scenario the two-dimensional models predict larger column ozone depletions at mid- and high-latitudes, but less in the tropics, than the global average predicted by one-dimensional models.

One important question that has been debated during the last couple of years is whether the magnitude of the predicted ozone change is a linear or non-linear function of atmospheric chlorine concentration. The issue is still somewhat unresolved, although it now appears from most one- and two-dimensional model calculations that ozone change is a linear function of atmospheric chlorine for atmospheric concentrations of chlorine of 25 parts per billion or less. Thus, sudden catastrophic global ozone depletions are unlikely if only small changes occur in the atmospheric concentrations of chlorine. However, this statement assumes that the models accurately represent the real world, yet prudence tells us that we should remember that these models are not perfect and that they cannot explain the observed large changes that are currently occurring in ozone over Antarctica during springtime, which we discuss below.

ATMOSPHERIC OZONE OBSERVATIONS

A crucial task for scientists is to assess the extent to which changes in global ozone have already taken place, and to compare the changes to what has been predicted by theory. The search for global ozone trends involves looking for small secular changes amidst the large natural variations that occur on many time scales. Observations of the total column content and the vertical distribution of ozone have been made for several decades using networks of different measurement techniques. Unfortunately, each of these observational techniques has certain limitations, which tends to restrict our confidence in the results. These limitations arise from factors such as the lack of continuity of reliable calibration and the uneven geographic distribution of stations. Statistical analyses of the data are required to identify small trends amongst high natural variability using data from relatively few stations.

In general, analyses for the trends in the total global column content of ozone, using data from the ground-based Dobson spectrophotometer network, show no statistically significant trend since 1970, which is in agreement with model predictions for the same period when the changes in all of the trace gases are taken into account. It should be noted that the values of total global column ozone in the last three years have exhibited significant variability. Abnormally low values of total column ozone were observed in 1983 following the eruption of El-Chichon and the largest El-Nino event this century. However, the values of total column ozone recovered in 1984, only to decrease significantly in 1985.

Trend estimates have also been made for the altitude profile of ozone from the network of stations using the Umkehr technique. Deriving an accurate trend for changes in the vertical distribution of ozone is more difficult than for the total column because there are fewer stations and the Umkehr measurements are very sensitive to the presence of aerosols in the atmosphere. Recent volcanic eruptions, such as that of El-Chichon, have deposited large quantities of aerosols into the stratosphere, and thus the Umkehr data must be corrected. After correcting the derived ozone amounts for the aerosol interference, an estimate of the ozone trend in the middle and upper stratosphere (30-40 km) gives a 2% to 3% decrease for the period 1970-80. The magnitude of the change is broadly consistent with the predictions of photochemical models, which predict that chlorine will have its maximum effect at this altitude.

A recent preliminary analysis of Nimbus 7 satellite Solar Backscatter Ultra-Violet (SBUV) data has indicated that there has been a statistically significant change in both the total column content (a decrease) and the vertical distribution (a decrease in the middle and upper stratosphere) of atmospheric ozone between 1978 and 1984. Further analysis of the data indicates that most of the change has occurred since 1981. It is crucial to evaluate whether the decrease is due to natural causes, such as a decrease in solar radiation, the 1982 eruption of El-Chichon, or the 1982 El-Nino event, or whether it is due to human activities such as the use of chlorofluorocarbons. At this time, any of these explanations are plausible.

Important new observational evidence on ozone changes has recently been obtained. Data from a single Dobson instrument at Halley Bay 76°S, 27°W has indicated a considerable decrease (greater than 40%) in the total column content of ozone above Antarctica during the spring period (late August to early November) since 1957, with most of the decrease occurring since the mid-1970s. Satellite measurements using both the Nimbus 7 Total Ozone Monitoring System (TOMS) and the SBUV instruments have verified this trend over Antarctica since 1979 and have demonstrated the spatial and temporal variations in this feature. Plate 1 shows the decrease in the monthly mean concentrations of the column amount of ozone over Antarctica in the month of October from 1979 to 1985. Similar ozone changes are not observed over the Arctic. Satellite measurements of the vertical distribution of ozone, nitrogen dioxide, water vapor, and aerosols over Antarctica during the 1985 spring period have been obtained using the Stratospheric Aerosol and Gas Experiment (SAGE), which was launched in 1984 on the Earth Radiation Budget Satellite (ERBS). This data is now being analyzed and interpreted. It is not yet evident whether the behavior of ozone above Antarctica is an early warning of future changes in global ozone or whether it will always be confined to the Antarctic because of the special geophysical conditions that exist there. While it has been suggested that these Antarctic ozone decreases are caused by increasing concentrations of chlorine in the stratosphere, no credible mechanism has been demonstrated--since the models using present chemical schemes are unable to simulate this effect. Until the processes responsible for the decrease in spring-time Antarctic ozone are understood, it will not be possible to state with any certainty whether it is a precursor of a global trend. A number of theories, some chemical, others dynamical, have been advanced to explain these observations. A major field measurement has been planned to take place in 1986 to study the ozone layer above Antarctica. This campaign is being cosponsored and coordinated by NASA, the National Science

Foundation, the National Oceanic and Atmospheric Administration (NOAA), and the Chemical Manufacturers Associations (CMA).

MODEL RELIABILITY

There are now observations of increases in the atmospheric concentrations of the gases predicted to affect ozone, and there are observations indicating that the total column content of ozone has changed significantly on a regional and, possibly, global scale. In addition, there are indications that the vertical distribution of ozone may also have changed. The question still remains concerning the reliability of the model used to predict ozone change. Given that we cannot directly test the accuracy of a prediction of the future state of the atmosphere, including the distribution of atmospheric ozone, we must test the models by trying to simulate the present atmosphere (including the distribution of atmospheric ozone) or by trying to simulate the evolution of the atmosphere, in particular ozone, over the past few years. This is done by comparing model predictions with atmospheric observations.

We should note that nearly all the key chemical constituents that are predicted to be present in the atmosphere (and that are important in ozone photochemistry) have now been observed. In general, the models predict the distribution of the chemical constituents quite well. However, the measurements are not adequate for critically testing the reliability of the photochemical models. Close examination of the intercomparison of measurements and model simulations of the present atmosphere reveal several disturbing disagreements. One of the major disagreements appears to be that <u>modelled</u> ozone concentrations are typically 30% to 50% lower than <u>measured</u> ozone concentrations in the upper stratosphere--where it should be easiest to predict the concentration of ozone (Figure 7) and where chlorine is predicted to have its maximum effect. These types of disagreements limit our confidence in the predictive capability of these models.

In the end, our predictive capability will be tested by measuring the changes taking place in the atmosphere. This will require careful measurements of critical species to be carried out over long time periods (i.e., decades). NASA, NOAA, and the Chemical Manufacturers Association recently cosponsored a workshop to design an "Early Detection of Stratospheric Change" system. This system would be designed primarily to provide the earliest possible detection of changes in the chemical and physical structure of the stratosphere, and the means to understand them. Implementation of such a system is a high priority.

CLIMATE CHANGE

As stated earlier, the observed increase in atmospheric concentrations of the CFCs, CH_4, CO_2, and N_2O also have direct implications for the earth's radiative balance through the so-called greenhouse effect. These gases absorb infrared radiation in a part of the spectrum for which the atmosphere is otherwise transparent. Presently, and in the near future, changes in the concentrations of trace gases other than CO_2 are thought to be contributing to the greenhouse warming of the earth's surface and lower atmosphere by an amount that is about equal to that due to changes in the concentration of CO_2 (Figure 8). The cumulative effect of the increase in all trace gases for the period 1850-1980 is a predicted equilibrium warming (ignoring the heat

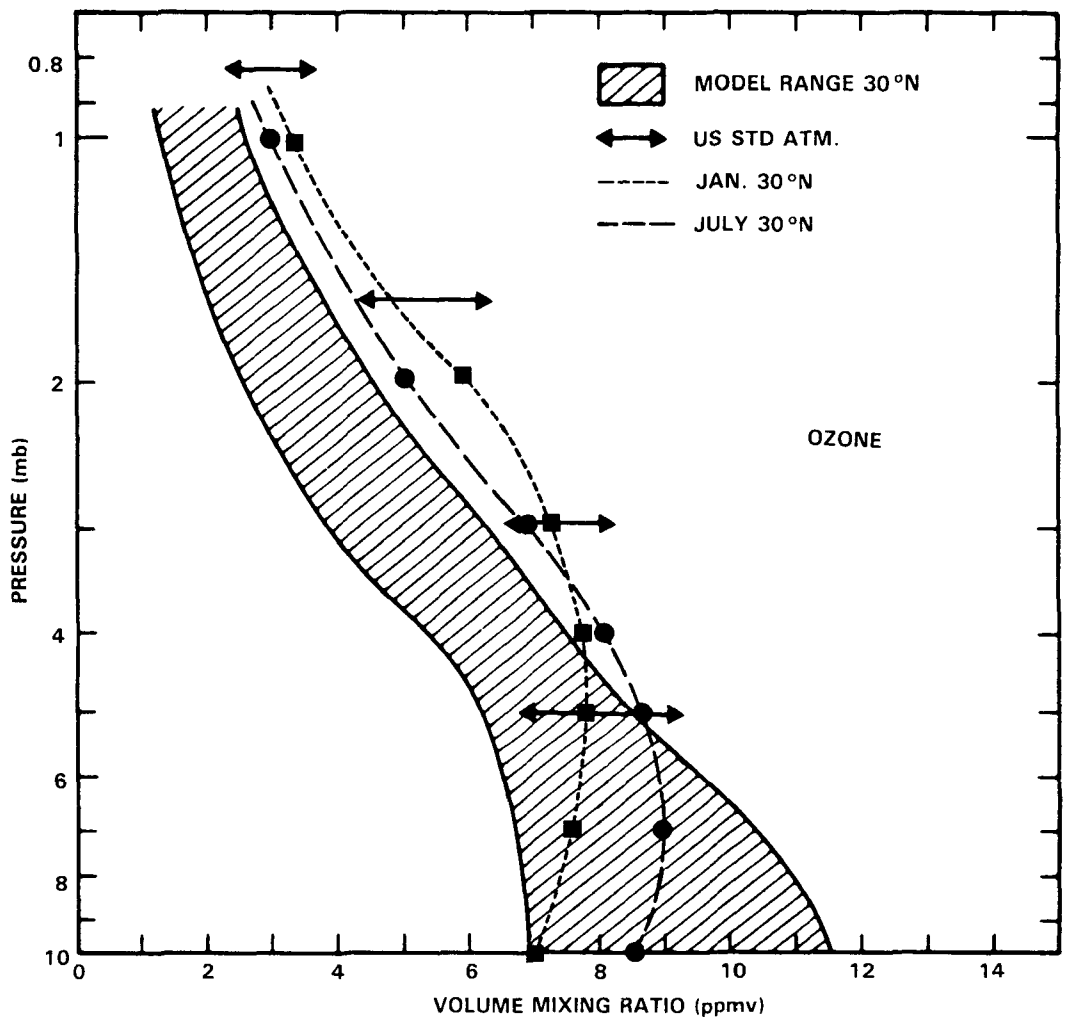

Figure 7. Vertical distribution of the ozone mixing ratio in the upper stratosphere. The shaded area included 2-D model results obtained for winter and summer conditions at 30°N. The O_3 mixing ratio given by the US Standard Atmosphere as well as representative observations at 30°N for January and July are also indicated.

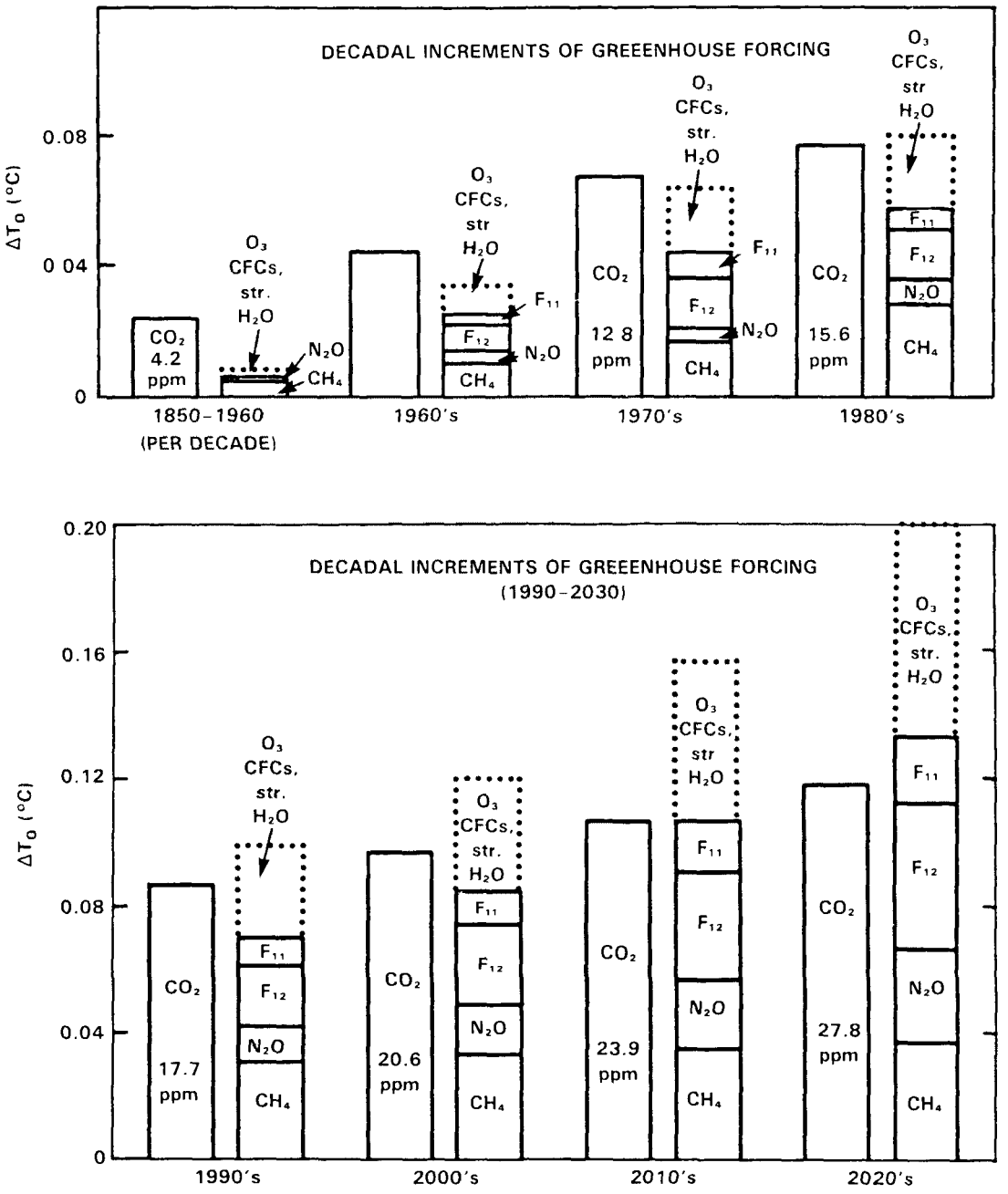

Figure 8. Decadal additions to global mean greenhouse forcing of the climate system. ΔT_0 is the computed temperature change at equilibrium ($t \to \infty$) for the estimated decadal increases in trace gas abundances, with no climate feedbacks included.

capacity of the oceans) in the range of 0.7°-2.0°C, about half of which should have occurred to date. Model calculations indicate that the greenhouse warming predicted to occur during the next 50 years should be about twice that which has occurred during the previous 130 years. Thus, problems of ozone change and climate change should be considered together. It is also apparent that what has been previously thought of as the CO_2/climate problem should more properly be thought of as the trace gas/chemistry/climate problem.

SUMMARY

Given what we know about the ozone and trace gas/chemistry/climate problem, we should recognize that we are conducting a global-scale experiment on the earth's atmosphere without fully understanding the consequences. Significant progress has been made in our understanding of the physical and chemical processes that control the distribution of atmospheric ozone. However, we must recognize that significant uncertainties in our knowledge remain, and that these can only be resolved through a vigorous program of research. It is essential that the U.S. government and industry continue their strong commitment to study the earth's atmosphere, and that the scientific agencies continue their close collaboration at both the national and international level.

Ozone Perturbations Due to Increases in N_2O, CH_4, and Chlorocarbons: Two-Dimensional Time-Dependent Calculations

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ABSTRACT

Time-dependent ozone perturbation estimates are performed in a 2-D diabatic circulation model with ozone photochemistry. Future increases in the emissions of N_2O, CH_4, and the chlorocarbons $CFCl_3$, CF_2Cl_2, $CHClF_2$, $C_2Cl_3F_3$, CH_3CCl_3, and CCl_4 are considered. The altitude variation of the calculated ozone change in the upper stratosphere is within the uncertainty limits of the observed trend reported from Umkehr data for the period 1970-80 when the effect of temperature changes from CO_2 is included. Future ozone predictions consider only the photochemical response to source gas increases. For the integrations through the year 2030, four different emission scenarios for chlorine releases have been used. The average global ozone column would be reduced by 6.5% in the year 2030 compared to the 1960 level, if chlorine emissions are increased by 3.0%/yr and the concentrations of N_2O and CH_4 increase by 0.25 and 1.0%/yr, respectively.

In a case with low chlorocarbon emissions and a modest reduction in the total ozone column, the altitude profile is highly distorted. In addition, the latitude gradients are pronounced. If all the chlorocarbon emissions are stopped in the year 2000, a minimum in the total ozone column density would be reduced at different times at low and high latitudes. Although the average total global density would decrease for almost 10 years, the minimum would be reached after only 5 years at high latitudes where the depletion in total ozone would be largest. Accelerated ozone depletion would occur approximately when the total chlorine exceeds the amount of nitrogen in the stratosphere. This situation would not occur before the year 2030 in any of the model runs with the scenarios selected here. Ozone predictions were performed for an additional period of 50 years for the chlorocarbon scenario with the highest emissions. In this case, nonlinear growth in ozone depletion was projected to occur after the middle of the next century.

INTRODUCTION

Possible modifications of stratospheric ozone have attracted considerable interest in the last decade. Increased concentrations of stratospheric chlorine from industrial emissions of chlorocarbons, as well as increased levels of nitrogen accompanying an observed increase in the concentration of nitrous oxide (N_2O), have the potential to significantly deplete ozone. An increase in CO_2 and other radiatively active trace gases that lead to lower temperatures in the stratosphere will have the opposite effect through a decrease in ozone destruction. Enhanced ozone production is believed to take place in the troposphere due to the observed increase in methane (CH_4).

A number of ozone perturbation experiments have been performed using two-dimensional (2-D) computer models (Brasseur and Bertion 1978; Vupputuri 1979; Borucki et al. 1980; Haigh and Pyle 1982; Gidel, Crutzen, and Fishman 1983; Whitten, Bourucki, and Woodward 1983; Haigh 1984; Solomon, Garcia, and Stordal 1985). In a recent study (Isaksen and Stordal 1986) we used the present 2-D diabatic circulation model for steady-state ozone perturbation studies. Perturbations due to increases in CH_4 and N_2O, as well as a wide range of chlorine levels were investigated. The main features in the distribution of ozone changes were similar to those obtained by the models of Garcia and Solomon (1983), Solomon and Garcia (1984), and Ko et al. (1985), as presented in the National Aeronautics and Space Administration/World Meteorological Organization (NASA/WMO) (1986) compilation. This is not surprising since the transport representation is similar in the model (as discussed in NASA 1986). It deviates from most 2-D models using the Eulerian transport formulation with higher diffusion (e.g., Gidel et al. 1983) in important ways. For instance, a more pronounced latitudinal gradient in the chlorine-induced reductions of the total ozone column is predicted when the diabatic circulation and slow diffusion are used for tracer transport. All the above calculations are based on steady-state assumptions. Time-dependent long-time simulations have so far been confined to one-dimensional (1-D) models.

In this paper, a set of 2-D time-dependent experiments is described, to our knowledge the first reported since the experiment of Vupputuri (1979). He calculated ozone changes through the year 2015 under the assumption of constant releases of chlorofluoromethanes at 1975 levels. Our understanding of the photochemistry of the stratosphere has increased considerably over the last few years, leading to ozone-perturbation estimates that differ considerably from what Vupputuri obtained. Besides offering a more realistic tracer transport than 1-D models, 2-D models employ predictions of future ozone variations at specific latitudes. When the time history of the future ozone distribution is considered, the difference in latitudinal response is a main concern since the ozone depletion has been shown to increase significantly from lower to higher latitudes. As discussed in Stordal, Isaksen, and Horntveth (1985), the model gives a credible description of the distributions and lifetimes of long-lived gases, such as O_3, N_2O, CH_4, CF_2Cl_2, $CFCl_3$, and CCl_4.

A set of scenarios of the future evolution of some source gases has been selected for the present study. It has been necessary to restrict the number of cases. Four different scenarios for the chlorocarbons have been selected in combination with increases in N_2O and CH_4. The source gas scenarios adopted are presented in the Ozone Loss Mechanisms section. As the observed

CH_4 increase is not well understood, it is far from certain that the present rate of increase (1% per year) will continue over the time period considered in these calculations. One of the experiments has therefore been performed with future CH_4 constant at the 1980 level, making a total of five scenarios that have been selected for model simulations for the time period 1980-2030. The reference year for the model study is 1960, when the time-dependent calculations were started.

The present model extends from the surface to 50 km altitude, and includes the photochemistry of oxygen, hydrogen, nitrogen, and chlorine compounds. The distribution of ozone-loss rates due to each of these chemical families is important for the response in ozone to changes in the chemical composition of the stratosphere. Photochemical terms for the long-lived tracers are calculated four times a year when fully diurnal computations are undertaken. The photochemical data have been updated in accordance with the latest NASA/Jet Propulsion Laboratory (JPL) (1985) recommendations. In the discussion on ozone balance in the Ozone Loss Mechanisms section, latitudinal as well as altitudinal variations in the influence of each of the main ozone loss cycles are demonstrated.

In the middle and lower statosphere, nitrogen species are believed to contribute largely to the loss of ozone. In our previous study we also demonstrated that nitrogen compounds have a strong influence on the efficiency of ozone depletion due to chlorine increases (Isaksen and Stordal 1986). In light of reports that 2-D diabatic circulation models tend to underestimate the amount of odd nitrogen present in the lower stratosphere (NASA/WMO 1986; Ko et al. 1986), we have included a discussion of how well nitrogen is distributed in the lower stratosphere in the Ozone Loss Mechanisms section.

In the section on the trend in ozone for the period 1970-80, we compare estimated changes in upper tropospheric ozone as compared to the observed decadal trend in ozone in the period 1970-80, as reported in NASA/WMO (1986). Estimated changes in ozone during the decade based on Umkehr measurements at thirteen observational locations were reported.

Results describing the future evolution of the tropospheric and stratospheric ozone are described in the section titled Time-Dependent Future Ozone Experiments. Figures showing the globally and seasonally averaged total column, latitudinal and yearly variation of the ozone columns, as well as altitudinal distributions are presented. For some of the scenarios, the effects of a cease of reductions in chlorine reductions are demonstrated (see the section on the response in ozone to future regulations in chlorine releases), which could offer useful information with respect to future emission control.

All ozone predictions presented in this study represent the photochemical response to source gas increases except upper stratospheric depletion between 1970 and 1980, which includes cooling effects from CO_2. Feedback from changes in temperatures and tracer transport have not been considered.

SOURCE GAS SCENARIOS

Chlorocarbons

Observations show that the concentrations of several halocarbons in the atmosphere are increasing. In an extensive measurement program (Atmospheric Lifetime Experiment [ALE]), the concentrations of $CFCl_3$, CF_2Cl_2, CCl_4, and CH_3CCl_3 have been monitored at five coastal or island stations exposed to little polluted air (Prinn et al. 1983a). A steady increase in these components has been reported at all locations during the observational period 1978-81.

The chlorocarbons included in the present study are methyl chlorine (CH_3Cl), carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), and the chlorofluorocarbons F11-$CFCl_3$, F12-CF_2Cl_2, F22-$CHClF_2$, and F113-$C_2Cl_3F_3$. These compounds are believed to be the main sources of future stratospheric chlorine. The source for these gases (except CH_3Cl) is industrial releases. As the residence times are of the order of 50-100 years (see Stordal, Isaksen, and Horntveth 1985), except CH_3CCl_3 which has a residence time of about 10 years, the present increases are due to past as well as present emissions.

Release rates of chlorocarbons for the period 1960-80 are taken from: Cunnold et al. (1983b, $CFCl_3$); Cunnold et al. (1983b, CF_2Cl_2); Prinn et al. (1983b, CH_3CCl_3); and Simmonds et al. (1983, CCl). The atmosphere was assumed to initially (1960) contain 0.6 ppb of CH_3Cl and 0.1 ppb of CCl_4, resulting in a 1 ppb in content of stratospheric chlorine. The CH_3Cl surface flux needed to obtain the 1960 mixing ratio was kept constant in all the computations. For $CFCl_3$, CF_2Cl_2, and CH_3CCl_3, the integrations were started in 1960 with zero abundances and releases corresponding to amounts accumulated in the years prior to 1960, which is a reasonable assumption since the releases were small before 1960.

Scenarios for future industrial releases are necessarily uncertain. We have performed experiments with four different chlorocarbon scenarios, listed in Table 1. Our computations are partly based on the evaluation of Quinn et al. (1986) from whom we have adopted emissions for $CFCl_3$, CF_2Cl_2, $CHClF_2$, $C_2Cl_3F_3$, CCl_4, and CH_3CCl_3 in the period 1985-2030. Based on economic models that consider industrial usage, competitive products, and economic and population growth, they developed seven scenarios for the chlorocarbons. In our scenario C we have used emission rates between the values in their two highest scenarios (VI and VII). As can be deduced from Table 2, the releases of the largest contributions to stratospheric chlorine, CF_2Cl_2 and $CFCl_3$, are projected to increase 3.5% and 5% per year, respectively, until the year 2000. Thereafter the growth rate declines and reaches 2% per year by the end of the period for both gases. Our scenario D is chosen to be identical to their scenario II. In this scenario the reduction in emission growth starts earlier (in the year 1990). By the end of the period in question, the growth is 1% per year for CF_2Cl_2 and $CFCl_3$. We have also included one scenario with constant emissions at 1980 levels (scenario A) as well as one with a steady 3% yearly increase in emissions after 1980 (scenario B). $C_2Cl_3F_3$ is not explicitly represented in the model. The release of this compound is added to the releases of CF_2Cl_2 (on a Cl base) since the two gases have similar photochemical characteristics (NASA/JPL 1985). Table 2 demonstrates that the releases of $C_2Cl_3F_3$ are modest compared to the CF_2Cl_2 releases.

Table 1. Source Gas Scenarios 1980-2030

N_2O : 0.25%/yr increase in the period.

CH_4 : Either 1.0%/yr increase or constant surface mixing ratio at 1980 level.

Chlorinated source gas emission (10^g/yr)

SCENARIO A: Constant releases 1980 level

$CFCl_3$: 265
CF_2Cl_2 : 485
CHF_2Cl : 82
CH_3CCl_3: 504
CCl_4 : 60

SCENARIO B: A 3%/yr increase in the emissions, starting with the values of scenario A in 1980

SCENARIO C: Emission rates between the values of scenarios VI and VII in Quinn et al. (1986)

Year	$CFCl_3$	CF_2Cl_2	CHF_2Cl	$C_2F_3Cl_3$	CH_3CCl_3	CCl_4
1985	325.4	449.3	52.9	114.0	509.7	153.1
1990	427.6	528.5	90.8	142.0	568.6	187.7
1995	553.4	624.9	130.2	198.2	634.3	205.7
2000	716.6	745.8	176.8	277.0	707.5	225.9
2010	1024.5	994.8	284.1	334.4	854.0	272.6
2020	1332.5	1266.0	407.4	403.6	1030.9	329.2
2030	1637.0	1564.1	543.0	484.1	1235.4	382.2
2040	2006.4	1919.2	732.7	573.0	1472.9	446.8
2050	2467.6	2341.8	918.7	683.0	1743.4	523.7
2060	2936.8	2770.4	1115.5	808.4	2063.5	613.8
2070	3439.9	3226.0	1310.0	956.8	2442.4	719.4
2075	3711.1	3472.3	1408.2	1033.0	2637.6	784.1

SCENARIO D: Emission rates as in scenario II in Quinn et al. (1986)

Year	$CFCl_3$	CF_2Cl_2	CHF_2Cl	$C_2F_3Cl_3$	CH_3CCl_3	CCl_4
1985	323.5	446.1	57.3	114.0	509.7	41.0
1990	421.8	519.3	74.5	142.0	568.6	41.0
1995	476.2	572.7	92.4	157.0	634.3	45.0
2000	522.0	611.0	111.3	180.0	707.5	49.4
2010	594.1	683.2	139.2	217.5	854.0	58.8
2020	656.8	762.7	156.6	262.9	1020.9	70.1
2030	725.3	852.7	172.1	317.7	1235.4	83.5

Table 2. Source Gas Scenarios 1960-80

N_2O	:	1980 level 305 ppb, 0.2%/yr increase in the period.
CH_4	:	1980 level 1.70 ppm, 1.1%/yr increase in the period.
CH_3Cl	:	1960 level 0.6 ppb, constant surface boundary flux.

Emissions for Chlorine Source Gases Taken From:

$CFCl_3$	:	Cunnold et al. (1983a)
CF_2Cl_2	:	Cunnold et al. (1983b)
CH_3CCl_3	:	Prinn et al. (1983b)
CCl_4	:	Simmonds et al. (1983)

Chlorocarbons decompose in the stratosphere, where chlorine (Cl) and chlorine monoxide (ClO) radicals catalytically destroy ozone. Reductions of the stratospheric ozone layer is therefore presumed to accompany a continued growth in the chlorocarbon release rates.

Nitrous Oxide

The atmospheric concentrations of nitrous oxide are increasing (e.g., Weiss 1981; Khalil and Rasmussen 1983). Natural as well as anthropogenic sources have been identified. The two main anthropogenic sources are fertilizers (Crutzen 1974; Logan et al. 1978) and combustion processes (Weiss and Craig 1976; Pierotti and Rasmussen 1976).

Weiss (1981) observed an increase of about 0.2% per year in the four-year period 1976-80 and suggested that this increase was due to increasing anthropogenic releases. In the present study this growth has been adopted for the entire period 1960-80 (Table 2). Isaksen and Stordal (1986) argued that the anthropogenic releases constitute only a small fraction of the total N_2O source at present. In the future the anthropogenic fraction can be expected to increase markedly and also play a more significant role in the total N_2O budget, causing an accelerated growth in N_2O. Despite this speculation, we take a more conservative approach; a yearly growth of 0.25% is assumed for future N_2O releases in accordance with the recommendation of Quinn et al. (1986).

N_2O has a long atmospheric lifetime (about 150 years, see discussion in Stordal, Isaksen, and Horntveth 1985) as the loss processes in the troposphere are very slow. In the stratosphere, N_2O decomposes, and is partly converted to oxides of nitrogen (NO_x) which catalytically destroy ozone. Future increases in nitrous oxide will therefore be associated with ozone reductions in the stratosphere.

The efficiency of stratospheric chlorine in reducing the atmospheric ozone layer depends strongly on the level of stratospheric NO_x through various interactions between the NO_x and Cl_x chemistry. N_2O increases will therefore also influence the ozone reduction due to the presence of Cl_x in the

stratosphere. The rates at which chlorocarbons and nitrous oxide are assumed to increase in combined scenario experiments thus play an important role in the estimation of future ozone depletion.

Methane

Atmospheric measurements have clearly established that the concentration of methane is increasing (Rasmussen and Khalil 1981; Blake et al. 1982; Khalil and Rasmussen 1982; Ehhalt, Zander, and Lamontagne 1983). Since 1979, methane data have been obtained from at least six measuring sites, including the continuous record from the Cape Meares Region (Khalil and Rasmussen 1983). After an increase of about 1.8% per year in the period 1979-82, a temporary decline in methane was obtained at this station. This feature was associated with an El Nino Southern Oscillation phenomenon (Khalil and Rasmussen 1985) and reduced the average trend in the period 1979-84 to about 1.0% per year. The increase in methane prior to about 1979 is more uncertain. From the period after 1965 values from 0.5% per year (Ehhalt, Zander, and Lamontagne 1983) to 1.7% per year (Rasmussen and Khalil 1981) have been reported. In this study we used an annual increase of 1.1% for the period 1960-80 (see Table 2).

Our understanding of the global methane budget is still insufficient. An extensive review of the present knowledge is presented in NASA/WMO (1986). The total sink is estimated to be approximately 450 TG/year (Isaksen and Hov 1986), due to the loss through reaction with the hydroxyl radical in the troposphere. Total production of methane should be approximately the same; it is commonly thought that there is a balance between total production and loss of methane in the atmosphere. The relative strength of each source is, however, highly uncertain (Ehhalt and Schmidt 1978; Khalil and Rasmussen 1983; Seiler 1984). The latitudinal distribution of these sources is also poorly known. It is therefore difficult to explain the current rise in methane, and predicting future evolution of methane concentrations in the atmosphere is highly uncertain. We have chosen here to assume a future annual increase of 1.0% (Quinn et al. 1986) in most of the scenarios, but we have also included a scenario with constant level of CH_4 in the future (see Table 1).

Through methane's interaction with tropospheric chemistry, increases in emissions will lead to increased ozone concentration in this region of the atmosphere. Methane also plays an important role in the partitioning between the chlorine constituent Cl, ClO, and HCl in the stratosphere. Future methane changes will therefore also affect chlorine species in the stratosphere and thereby the depletion of ozone through these species.

OZONE LOSS MECHANISMS

Chemical loss of ozone in the stratosphere is characterized by the efficiency of chemical cycles involving nitrogen, hydrogen, chlorine, and oxygen species. To avoid the strong coupling between the individual components, particularly among the oxygen and nitrogen species, but also in the chlorine cycles at the enhanced levels expected to appear in the future, we introduce an odd oxygen family quantity: $O_x = O_3 + O + O('D) - NO - Cl$.

The rationale for introducing such a numerical quantity is thoroughly discussed by Hesstvedt and Isaksen (1978) where it was applied to air

pollution modeling to avoid stiffness in the oxygen-hydrogen-nitrogen system. In our previous studies on stratospheric chemistry (Stordal 1983; Stordal, Isaksen, and Horntveth 1985; Isaksen and Stordal 1986), chlorine was added to the quantity, strongly improving the stiffness problem (and thereby allowing for longer time steps to be used in the chemical calculations). We have considered the following loss reactions in the oxygen, hydrogen, nitrogen, and chlorine cycles (the parenthesized number to the left-hand side of the reaction denotes the number of O_x molecules destroyed in the reaction):

R1	Oxygen:	(2)	$O + O_3 \rightarrow O_2 + O_2$
R2	Hydrogen:	(1)	$OH + O_3 \rightarrow HO_2 + O_2$
R3		(1)	$HO_2 + O_3 \rightarrow OH + O_2$
R4		(1)	$OH + O \rightarrow H + O_2$
R5		(1)	$HO_2 + O \rightarrow OH + O_2$
R6	Nitrogen:	(2)	$NO_2 + O \rightarrow NO + O_2$
R7	Chlorine:	(2)	$ClO + O \rightarrow Cl + O_2$

In our previous paper (Figure 3 in Isaksen and Stordal 1986) we demonstrated the strong variations with height in the relative importance of the different chemical families. There are also some marked latitudinal variations in their relative importances, which are demonstrated in Figures 1a-d, where the relative loss of ozone from the oxygen, hydrogen, nitrogen and chlorine families is given as a function of latitude and height. Most important are the latitudinal differences in ozone destruction by the nitrogen and the chlorine reactions, particularly because the concentrations of these two families probably will increase noticeably in the future. The figures represent the situation in 1980 when the chlorine content of the stratosphere still was low (about 2.3 ppb). Nevertheless it is seen that chlorine reactions become increasingly important going toward high latitudes, where they dominate upper stratospheric ozone loss in the present atmosphere (Figure 1d). Ozone loss by nitrogen species is systematically moved to lower latitudes as we proceed toward high latitudes. This will be of importance, not only for the response in ozone concentrations to increased levels of NO_x or Cl_x, but also to the latitudinal response in ozone due to simultaneous changes in NO_x and Cl_x (combined scenario studies). The efficiency of the chlorine cycle at high latitudes with these moderate Cl_x levels explains the fast, high-latitude response in upper stratospheric ozone and in total ozone to chlorocarbon perturbation that is discussed in this paper. It seems reasonable in this early state of ozone depletion, before chlorine reactions are the dominant loss process at low latitude, that the differences in depletions are largest at high and low latitudes.

The importance of the NO_x chemistry for the ozone loss in the middle and lower troposphere is clearly demonstrated in Figure 1c. In addition, NO_x plays a significant role for chlorine-induced ozone depletion through interaction with the chlorine chemistry (Isaksen and Stordal 1986). Ozone perturbation studies from chlorocarbon releases rely heavily on a proper representation of NO_x levels in the models used. Unfortunately, 2-D diabatic circulation models tend to underestimate NO_y (total odd nitrogen) levels in the lower stratosphere in equatorial regions compared to observations (NASA/WMO 1986). At higher latitudes and altitudes the agreement is better.

Ko et al. (1986) suggest that the discrepancy between observed and 2-D model calculated NO_y values can be removed by taking into account NO_y production by lightning. This production is efficient in the upper troposphere in equatorial regions, where a significant amount (compared to the stratospheric NO_y production from N_2O) can be transported up through the troposphere by the process of diabatic circulation applied in these 2-D models.

The NO_y distribution in the actual area is very sensitive, for instance, to the horizontal eddy diffusion coefficients applied in the model at this low latitude region in the lower stratosphere. Our 2-D diabatic circulation model tends to give NO_y levels in better agreement with observations even without a lightning source.

In Figure 2 we have taken one of Ko et al.'s figures showing the NO_y profiles at the Equator from their model along with observations presented by Callis, Natarajan, and Russell (1985) and included the NO_y profile from our model. In contrast to the model of Ko et al. (1986), our model underestimates NO_y only at very low latitudes. At the important 25-km level there is a very good agreement between our model and the measurements. The figure shows that there is in general a higher NO_y level in our model than in the model of Ko et al. (1986). The discrepancy between the models increases toward lower altitudes in the lower stratosphere. This is at least partly due to a balance between vertical advection and horizontal diffusion which is more in favor of the latter process in our model than in theirs.

TREND IN OZONE FOR THE PERIOD 1970-80

Trend estimates based on thirteen Umkehr stations indicate that there has been a statistically significant reduction in ozone between 1970 and 1980 in the upper stratosphere between approximately 30 and 40 km. This reduction is estimated to be on the order of 0.2%-0.3% per year (NASA 1986), and is most pronounced in the height regions where the chlorine chemistry has its strongest effect on the ozone (Figure 1d).

Although the Umkehr data are hampered by large uncertainties--the result is particularly sensitive to the corrections made for the aerosol burden in the stratosphere--they nevertheless represent important indications that chlorine-induced perturbations can be detected in the stratosphere. For this reason it is very important to compare the estimated ozone trends based on observations with model-calculated ozone depletion for the same period.

Figure 3 shows height profiles at 40°N for the decadal depletion from our 2-D model studies. Global trend estimates reported in (NASA/WMO 1986) are also given in the figure. Estimates with temperature feedback (curve 1) give upper stratospheric ozone depletion larger than what is deduced from Umkehr observations. We have, however, also done one model study where we include temperature changes between 1979 and 1980. The stratospheric temperature decrease adapted for this period is taken from one-dimensional model studies by Brasseur, DeRudder, and Tricot (1985). Their calculations are based on a combined scenario, where temperature decreases in the 1970-80 period are a result of increases in CO_2 and other trace species. We have assumed that approximately one-third of the estimated change up to 1983 given by Brasseur, DeRudder, and Trico (1985) takes place between 1970 and 1980. This gives temperature decreases of approximately 1°C in the 45-50 km region and less

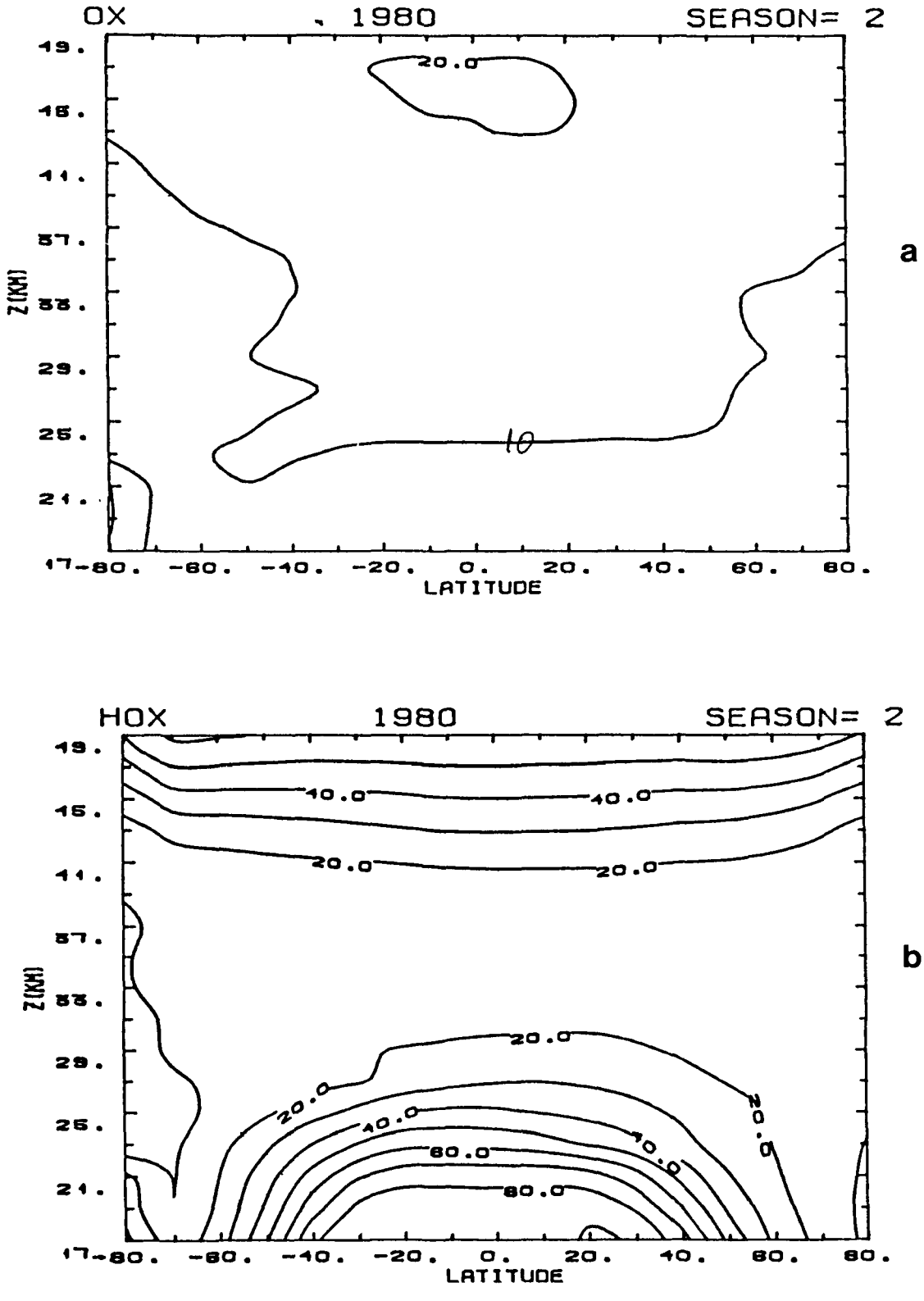
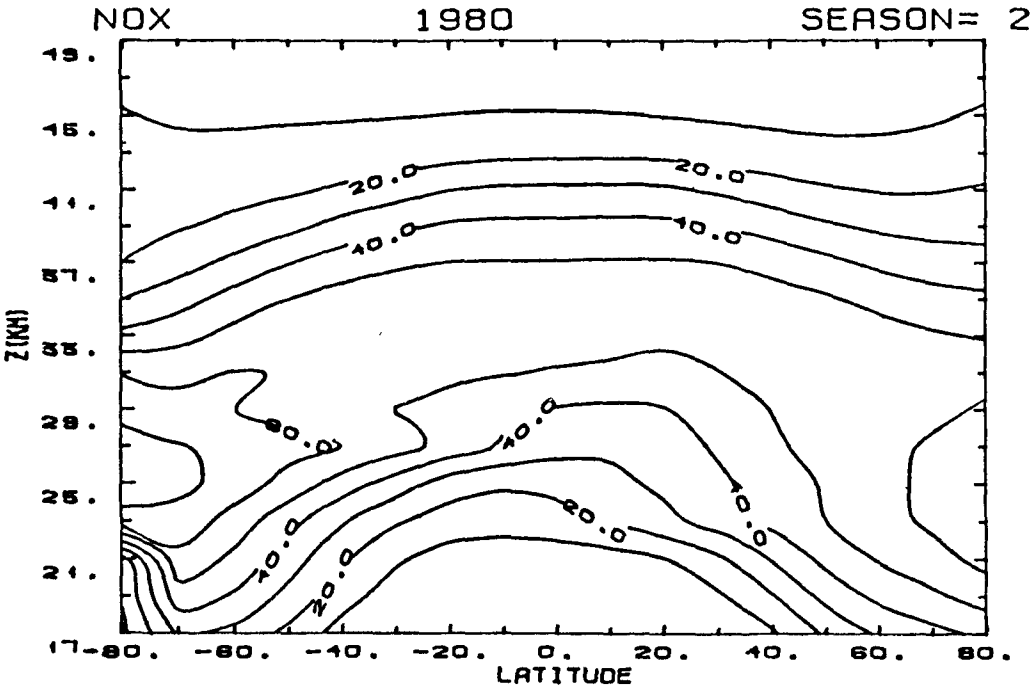


Figure 1. Percentage ozone loss rates due to O_x, HO_x, NO_x and ClO_x chemical cycles, relative to the total loss rates. Results are given as altitude-latitude contours for near equinox conditions.



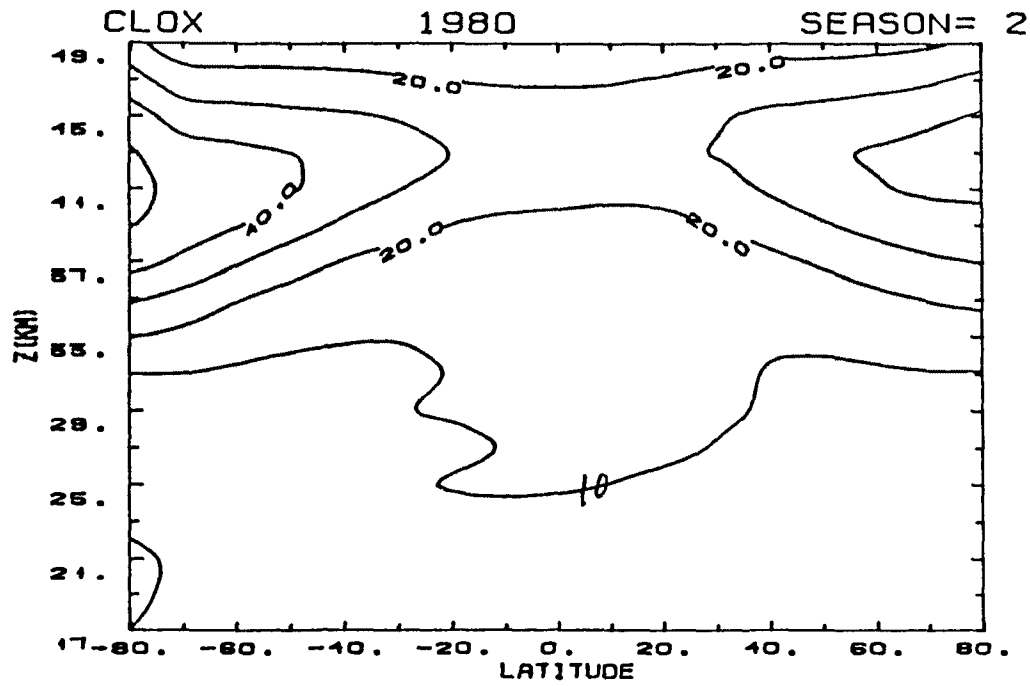


Figure 1 (Cont). The individual loss rates are computed from the following reactions:

O_x :	O	$+ O_3$	$\rightarrow$	O_2	$+ O_2$	(times 2)
HO_x :	OH	$+ O_3$	$\rightarrow$	HO_2	$+ O_2$	
	HO_2	$+ O_3$	$\rightarrow$	OH	$+ 2\,O_2$	
	OH	$+ O$	$\rightarrow$	H	$+ O_2$	
	HO_2	$+ O$	$\rightarrow$	OH	$+ O_2$	
NO_x :	NO_2	$+ O$	$\rightarrow$	NO	$+ O_2$	(times 2)
ClO_x:	ClO	$+ O$	$\rightarrow$	Cl	$+ O_2$	(times 2)

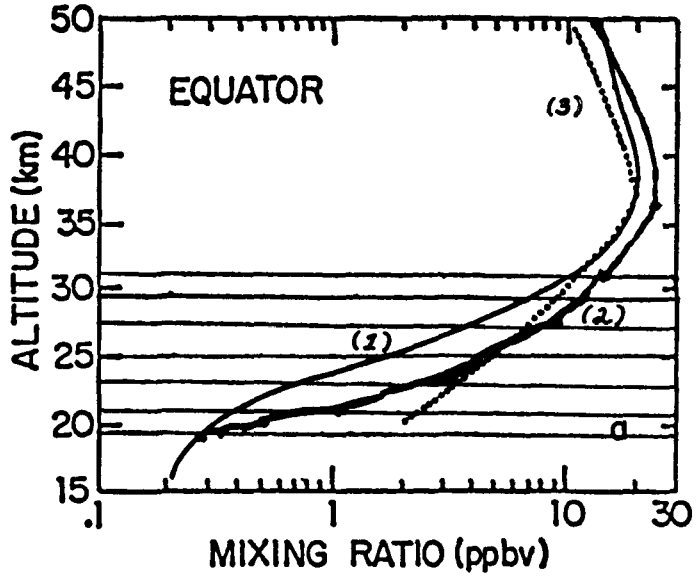


Figure 2. Comparison of the calculated NO_y profile at Equator in this model (curve 1) and the model of Ko et al. (1986) (curve 2) with the observed nighttime concentration of NO_2+HNO_2 (Callis et al., 1985; LIMS-data) (curve 3).

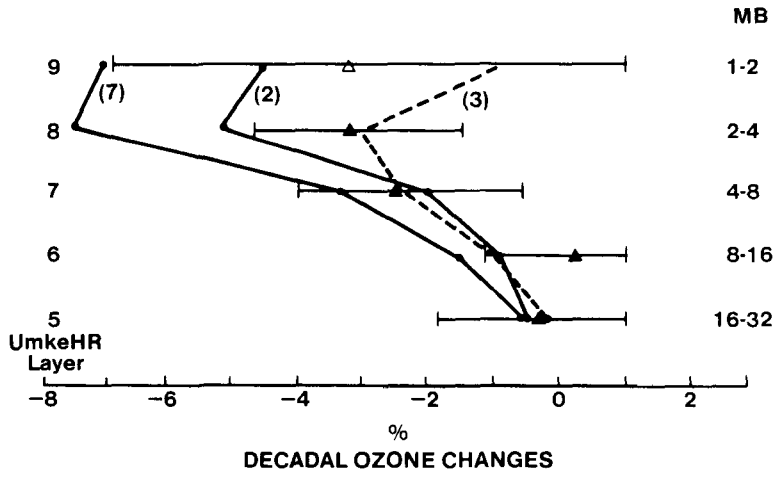


Figure 3. Calculated ozone depletion between 1970 and 1980 without (curve 1) and with (curve 2) temperature changes from radiatively active gases in the stratosphere. The adapted temperature change is taken from a 1-D model study by Brasseur, DeRudder, and Tricot (1985). Estimated global trends (Reinsel et al. 1983; Reinsel et al. 1984) are based on Umkehr data (triangles with error bars). A one-dimensional model calculation by Wuebbles, Luther, and Penner (1983) is included.

than 1°C below 35 km. When the temperature feedback is considered (curve 2), ozone depletion becomes approximately two-thirds of the estimated depletion when no temperature effect is considered.

The calculated profile is in better agreement with the result of the trend analysis when temperature effects are considered. However, almost twice as much depletion in the maximum area at high latitudes takes place than at low latitudes. Comparisons with observations are therefore strongly dependent on how representative the Umkehr observations are for mid-latitudes in the Northern Hemisphere (40°N).

The temperature effect from CO_2 is estimated to be more pronounced at low than at high latitudes, thus increasing the latitudinal differences in ozone depletion when temperature feedback is included. The reason is that nitrogen reactions that dominate ozone loss at low latitudes become less efficient at lower temperatures (Isaksen, Hesstevdt, and Stordal 1980), while this is not the case for chlorine reactions that dominate at high latitudes (see Figure 1d).

Temperature changes will have a pronounced effect on the trend in total ozone as shown in Table 3. Global ozone decrease between 1970 and 1980 is reduced from 0.62% to 0.22% when temperature feedback is included. If the observed methane increase is included there is even a slight increase (+0.03%) in the total column of ozone. At high latitudes (60°N) the depletion is pronounced in all three model studies discussed above.

Table 3. Time-dependent 2-D model calculations of ozone column depletion between 1970 and 1980. The numbers are for March and are given in %.

Global	-0.62	-0.21	+0.03
60° N	-1.84	-1.13	-0.88

case 1. Without temperature feedback and constant CH_4 release.
case 2. With temperature feedback and constant CH_4 release.
case 3. With temperature feedback and 2% annual increase in CH_4 releases.

TIME-DEPENDENT FUTURE OZONE EXPERIMENTS

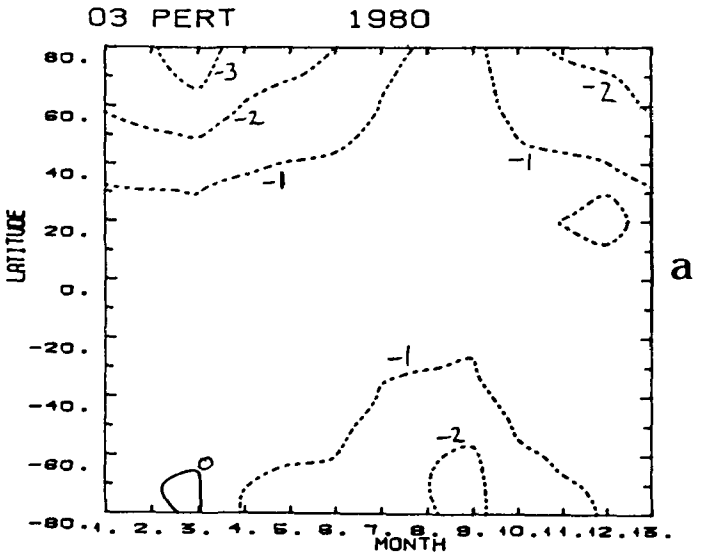
The distribution of ozone at three different points of time, the years 1980, 2000, and 2020, will be used to illustrate some main features in the development of ozone changes. Figures 4a-4f show the change in the total ozone column as a function of latitude and time of the year. The depicted changes result from a model run with a chlorine increase as assumed in scenario C. Simultaneous increases in N_2O and CH_4 (see Tables 1 and 2) are assumed. The figures also show latitude-altitude cross sections for the solstices (Northern Hemisphere winter) in the same years. The latitudinal, altitudinal, and yearly patterns are similar to those obtained in the steady-

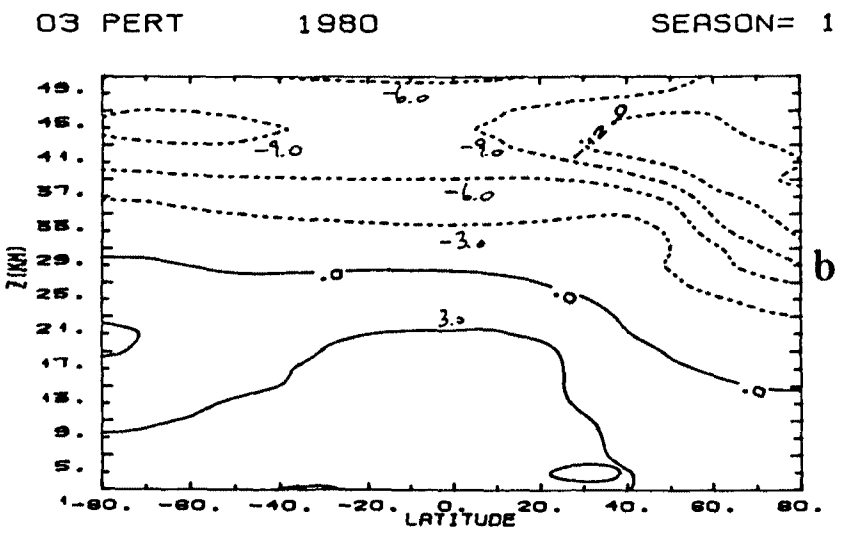
state ozone calculations reported earlier with this (Isaksen and Stordal 1986) and other 2-D models (especially the diabatic type models, NASA/WMO 1986): Ozone reductions take place in the middle and upper stratosphere as a result of chlorine chemistry (Figure 4d). The balance between active chlorine compounds (Cl and ClO), and the inactive compound HCl is shifted toward higher values of Cl and ClO. This is due to low CH_4 mixing ratios resulting from downward transport ($Cl+CH_4 \rightarrow HCl+CH_3$ is a main reaction converting active chlorine to HCl, see Solomon and Garcia 1984; Solomon, Garcia, and Stordal 1985). The maximum reductions are 15%, 40%, and 65% in the years 1980, 2000, and 2020, respectively. In the lower stratosphere at low and middle latitudes, increased penetration of UV radiation, resulting in the so-called self-heating effect, leads to increased levels of ozone. The growth in methane leads to increases in ozone in the entire troposphere, with maximum increases in the upper tropical troposphere. The model predicts a steady increase from 5% to 20% between the years 1980 and 2020.

In the lower stratosphere, where ozone is mainly transport-dependent, the isolines for constant percentage change slope poleward and downward due to the prevailing circulation pattern (see discussion in Solomon, Garcia, and Stordal 1985). This transport feature is the main cause for the marked latitudinal gradient in changes of the total ozone columns due to increased levels of chlorine and nitrogen in the stratosphere. Maximum depletions occur at high latitudes during winter and spring when the poleward and downward transport is most pronounced.

As Isaksen and Stordal (1986) point out, the latitudinal gradient in total ozone depletion caused by increases in stratospheric chlorine and nitrogen is enhanced by the effect of CH_4 increases. However, even if the low latitude ozone columns are only modestly changed, the height distribution of ozone is highly distorted. These changes are believed to have the potential for large climatological effects (NASA 1986). In the present (1986) atmosphere the estimated ozone changes are modest, as discussed in the section titled Trend in Ozone for the Period 1970-80. The situation may, however, be quite different already at the turn of the century, when large depletions in the upper stratosphere are estimated to take place. By that time, depletion in ozone column densities may exceed 5% at middle and high latitudes. Toward the year 2020 ozone depletion will continue to grow strongly, as a result of the pronounced increase in release rates of the chlorocarbons.

Figure 5 shows the time-dependent depletion in globally and seasonally averaged total ozone column densities. The curves represent the four chlorine scenarios (see Table 1). N_2O and CH_4 increases are assumed in all the results depicted in Figure 5. An ozone reduction of 1% compared to the 1960 level was reached between 1980 and 1985. The effect of temperature changes is not included in the results presented in this and the forthcoming sections. In the scenario where the chlorine releases are kept constant at 1980 levels, the ozone continues to deplete to about 2% by 2010. For the rest of the period, the global ozone is practically unchanged. In the three remaining scenarios with increasing chlorine releases, ozone columns in the entire period decrease. At the year 2020 the ozone reductions are 8.5% in the reference case, 5.0% in the low scenario, and 6.5% in the case with 3% annual increases in chlorine emissions. All values refer to average global reductions. These values can be compared to the time-dependent, 1-D study of Wuebbles (1983)





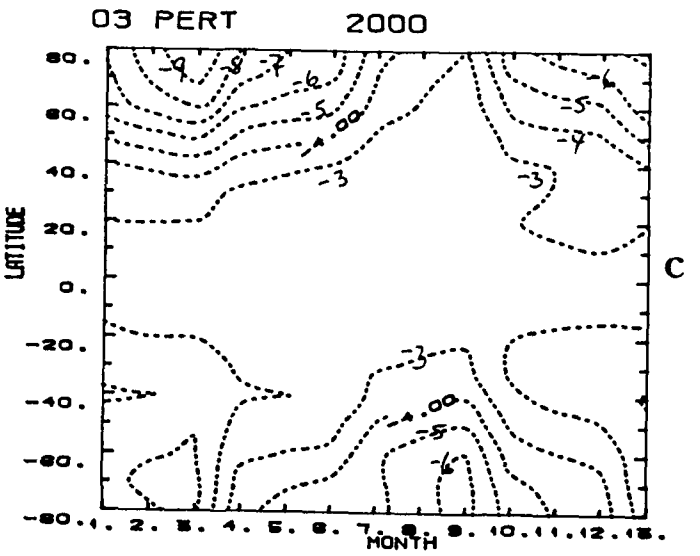
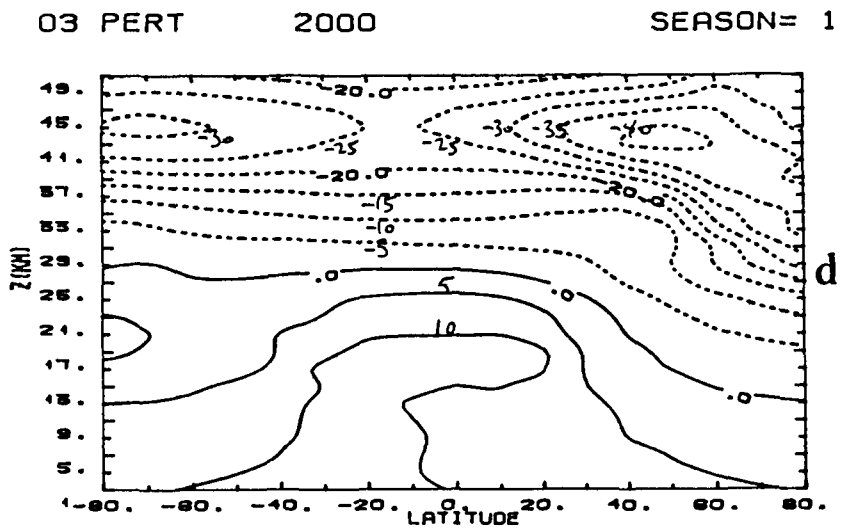


Figure 4. Percentage ozone changes in the year 1980 (see scenario Table 2) and the years 2000 and 2020 in the chlorine emission reference case with simultaneous increases in N_2O and CH_4 (see Table 1). Panels a, c , and e depict changes in the total ozone columns as a function of latitude and time of the year. Panels b, d, and f show altitude-latitude cross sections of local ozone changes for solstice conditions.



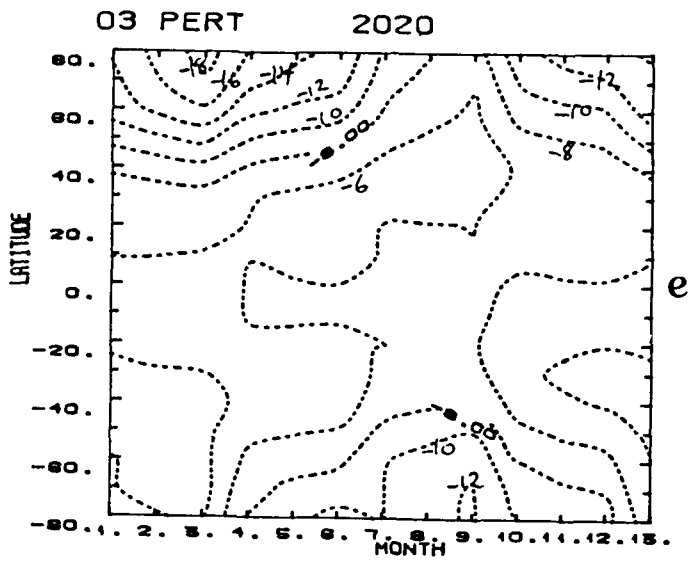
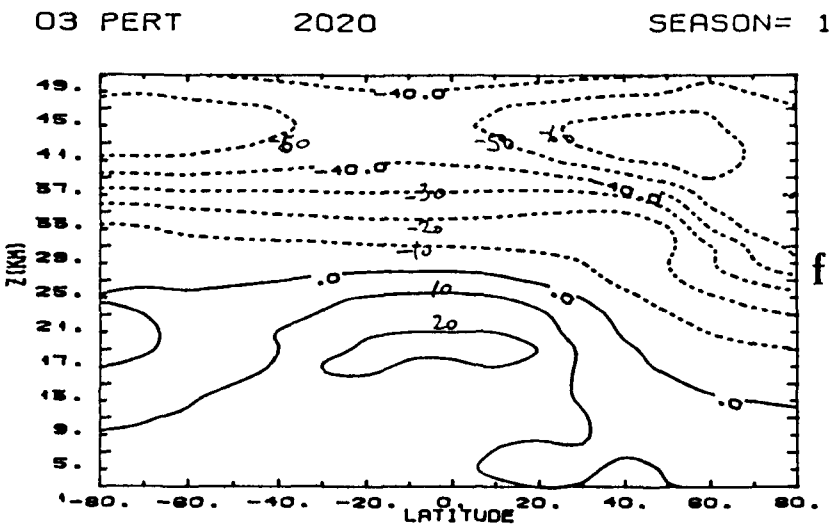


Figure 4 (Cont.)



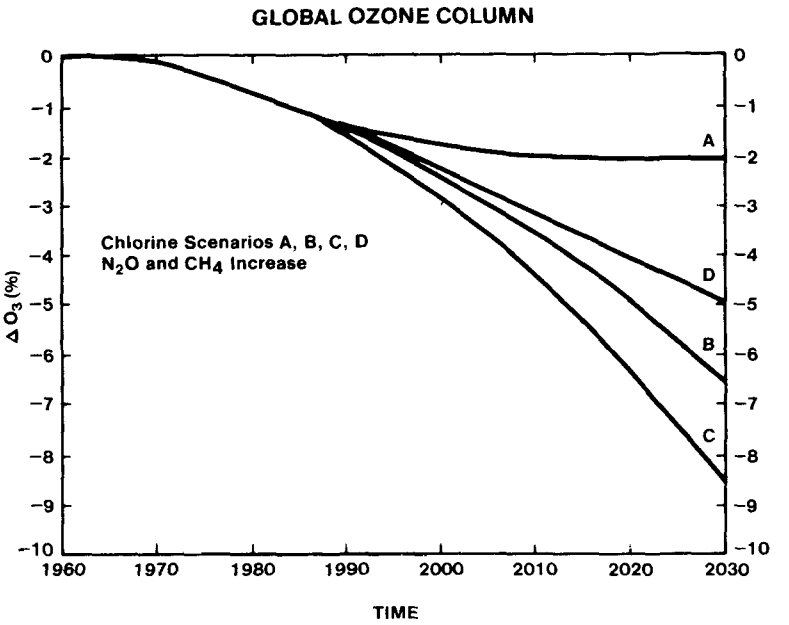


Figure 5. Calculated changes in globally and seasonally averaged ozone column as a function of time for the four chlorine scenarios (Table 1). Increases in N_2O (0.25%/yr) and CH_4 (1%/yr) have been included.

which has been run for our scenario C (Wuebbles 1986, private communication) with, as well as without, temperature changes. In the latter case the reductions are slightly less in his model compared to ours. The time evolution is, however, very similar in the 1-D and 2-D model runs.

Due to considerable uncertainties in the CH_4 scenario one experiment was performed with constant CH_4 releases (see the Source Gas Scenarios section). In this case, ozone is depleted substantially after 1980. In the year 2030, the reduction in the global ozone column density reaches 4.5% (see also Figure 6).

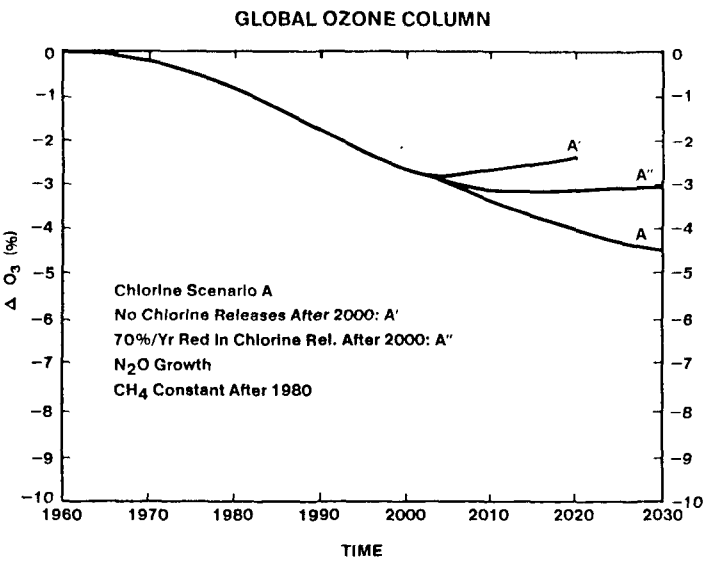


Figure 6. As Figure 5. Also included are ozone changes after the year 2000 when either a cease or annual reduction of 70% per year in emissions is introduced. CH_4 is kept constant after 1980.

Figure 4 shows a pronounced latitudinal gradient in the ozone changes. At high latitudes we also find marked seasonal variations. To illustrate the latitudinal effect we show time variations of ozone column densities at different latitudes in the constant chlorine release case (Figure 7). The spring values have been chosen since the latitudinal gradient is largest at that time of the year (see Figure 4). Even if the globally and seasonally averaged ozone column densities show small changes toward the year 2030, the column densities are still decreasing markedly at high latitudes. For instance, the reduction in the year 2030 is 8.3% at 60°N latitude and 3.8% at 40°N, while the global average reduction is only 2.0%.

The ozone reductions at 60°N latitude during spring are presented in Figure 8 for the four chlorine scenarios. In all cases N_2O and CH_4 increases are assumed. Ozone reductions are more than twice as large as the globally and seasonally averaged reductions shown in Figure 5. Particularly in the scenario C case, the springtime ozone reduction is pronounced at 60°N. At this latitude the ozone column density decreases at a rate of approximately 0.4% per year in the year 2030. Note that high latitude depletion shows little dependence on the scenarios chosen up to year 2000. The depletion is pronounced in all four cases, contrary to what is seen for the global average reductions (Figure 7).

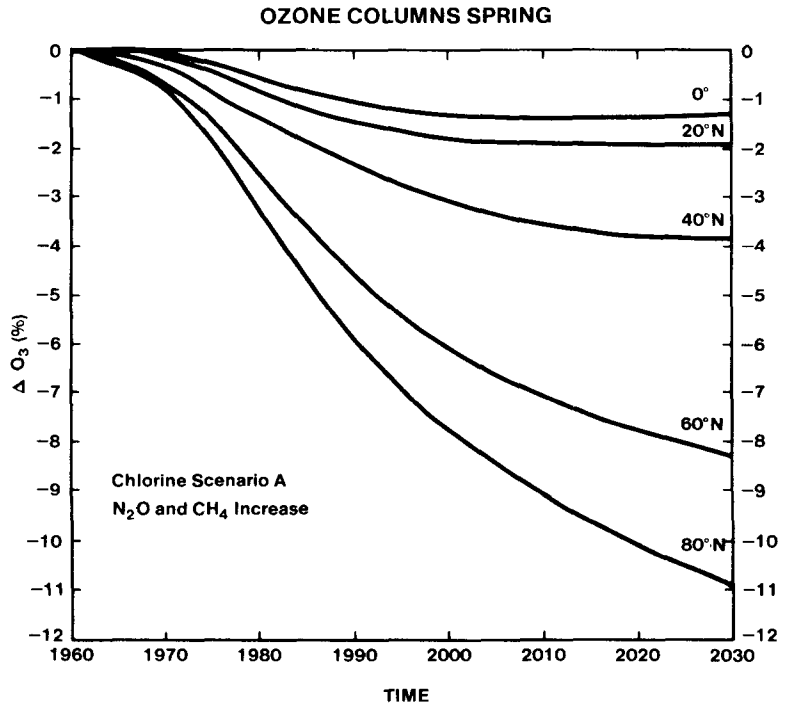


Figure 7. Changes in total ozone column with time for various latitudes. The results are for the spring in the case of 1980 level constant chlorine emission and growth in N_2O and CH_4.

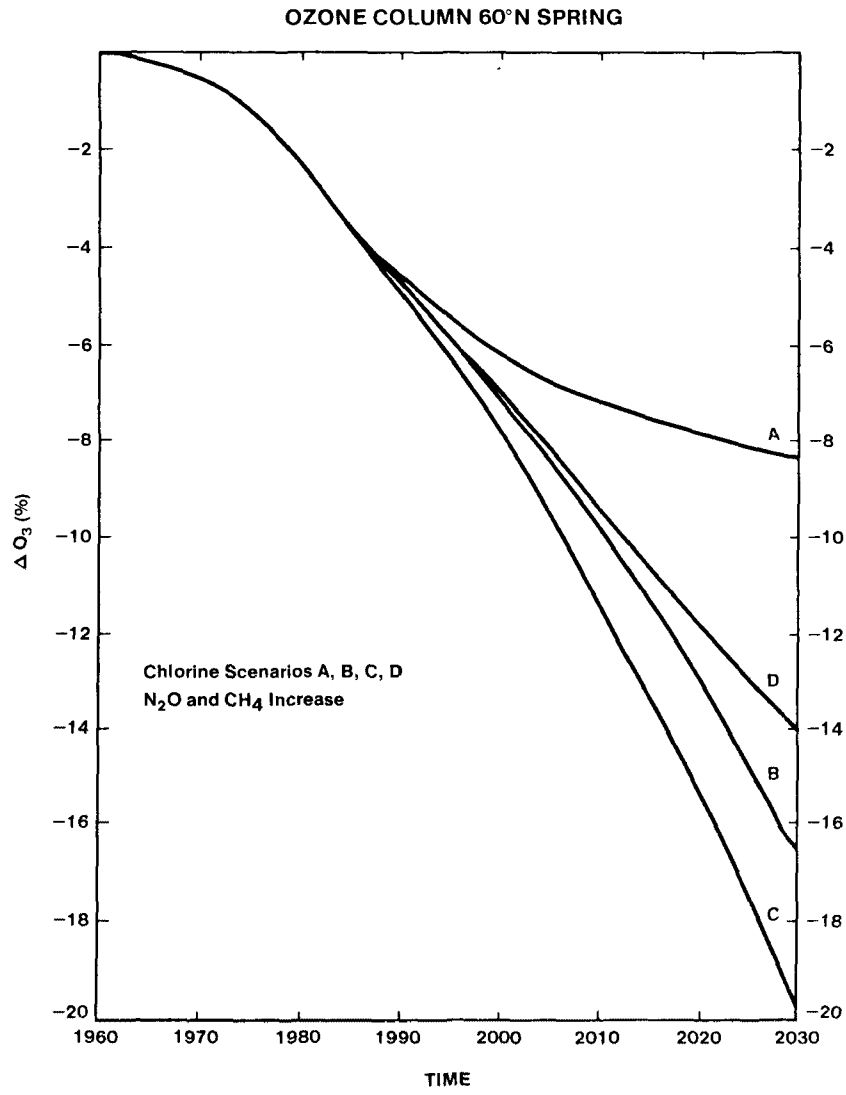


Figure 8. As Figure 5, but for the ozone column at 60° during spring.

The most dramatic ozone reduction takes place at high latitudes in the upper stratosphere (see Figure 4). Figure 9 compares local ozone changes with time at the 43 km level at 60°N during the winter for different scenarios. In all cases the ozone reduction is more than 30% by the turn of the century, and the depletion continues towards the year 2030. The reductions range from 45% in scenario A to 72% in scenario C.

Based on what has been shown in the previous two figures, it can be concluded that the ozone depletion at high latitudes in the upper stratosphere will be pronounced toward the beginning of the next century regardless which scenario unfolds. This statement applies to total column ozone as well as local depletion.

Temperatures are expected to change in the future as a result of an altered distribution of radiatively active gases. Predicted ozone reductions for the middle and upper stratosphere will lead to temperature reductions, as will CO_2 and other radiatively active gases that are increasing in the atmosphere (see, e.g., Ramanathan et al. 1985; NASA/WMO 1986). These temperature changes will influence the ozone distribution, as we have seen in Figure 3, leading to smaller ozone reductions from increases in stratospheric chlorine and nitrogen.

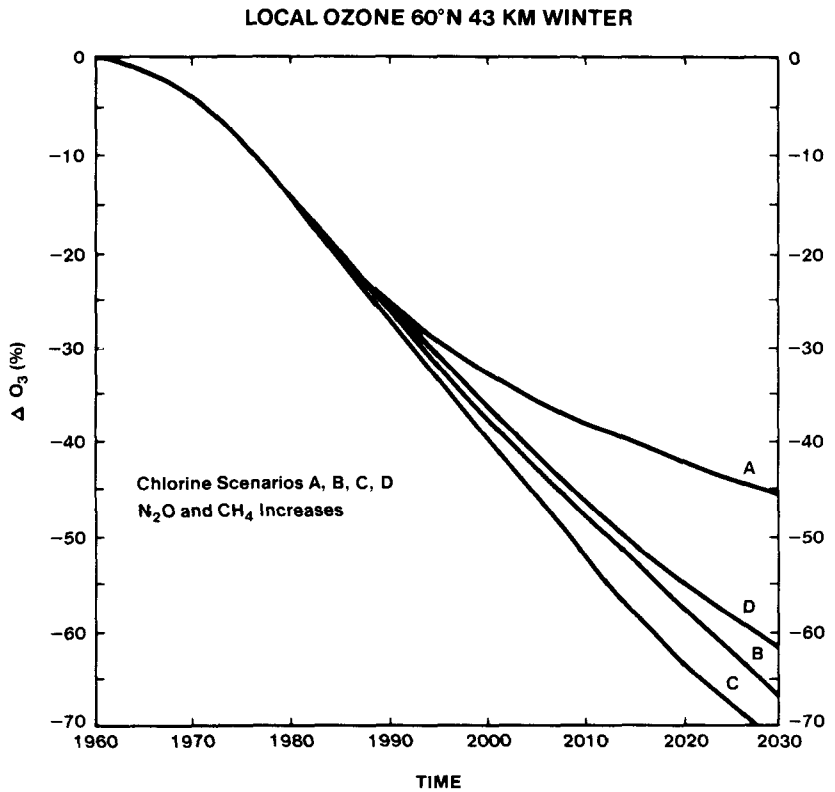


Figure 9. As Figure 5, but for local ozone densities at 60° N at the 43 km level during winter.

It is also likely that when the stratospheric temperature distribution is altered, changes in atmospheric circulation will take place, which in turn will influence the calculated ozone distribution. Ozone is jointly controlled by dynamical and photochemical processes. Even in regions where the ozone chemistry is fast, the dynamics can be of importance through the distribution of other long-lived species. The works of Fels et al. (1980) and Schoeberl and Strobel (1978), however, indicate a thermal rather than dynamical response to O_3 and CO_2 temperature perturbations. Their findings support the approach taken in this study, where we have used fixed dynamics in all the calculations. In their study, Fels et al. (1980) assumed uniform perturbations in O_3 and CO_2, making the application of their results somewhat uncertain for the O_3 perturbations presented in this paper.

RESPONSE IN OZONE TO FUTURE REGULATIONS IN CHLORINE RELEASES

The results presented in this and other studies show that large ozone depletions, especially at high latitudes (see below), will take place early in the next century if the chlorine emissions continue to grow. Extended emission control could then be required. In some experiments we have therefore studied the effect of reductions in chlorine releases. In Figure 10 the effect of stopping all chlorine releases is demonstrated. In two of the cases, the constant 1980 level release case (scenario A) and the 3% yearly emission increase case (scenario B), the emissions are assumed to come to a halt in the year 2000. (However, N_2O and CH_4 are assumed to continue increasing.) In both cases the globally and seasonally averaged ozone column density continues to decrease for 5-10 years. The relatively efficient recovery of the ozone layer after chlorine releases are stopped is a result of the continued increase in CH_4 releases after the year 2000.

Figure 6 shows that in the case with a constant CH_4 concentration the recovery of the ozone layer is slower. Obviously the future CH_4 evolution will have a pronounced influence on the recovery of the ozone column after a potential stop in chlorine releases. In the experiment described in Figure 6, constant releases of chlorine source gases have been assumed in the period 1980-2000 (scenario A). If chlorine emissions are stopped in the year 2000, the ozone would not relax back to the 1960 situation, mainly due to N_2O increases that have been assumed (also after the year 2000). In the period 2020-30 in this experiment, ozone continues to recover in the upper stratosphere due to decreases in stratospheric chlorine. In the middle and lower stratosphere there is a weak ozone reduction, mainly attributed to the N_2O growth, compensating for the production in the upper stratosphere such that the globally averaged total column is almost constant throughout the period.

So far results of a total removal of chlorine emissions have been demonstrated. A prompt cease in the emissions at a certain time, as we have assumed in the year 2000, must be considered unlikely. A gradual reduction of the emissions could be more conceivable. A scenario with a 7% yearly decrease in CFC emissions starting in the year 2000 (after constant release from 1980, scenario A) is therefore included in Figure 6 in the constant CH_4 case. This case is identical to scenario IX in the Organization for Economic Cooperation and Development (OECD) (1981) report. In the particular case it takes about 15 years to reach a minimum in ozone column densities, and the increase thereafter is extremely slow, in agreement with the 1-D calculations of Wuebbles (1983). Thirty years after the implementation of an emission reduction, the global ozone depletion would be 3.1%, compared to 4.5% in the case without emission reductions.

As discussed in the previous section (Figure 7), the ozone column is projected to decay more rapidly at higher than at lower latitudes. Correspondingly, when chlorine releases are stopped, the increase will be faster. This is demonstrated in Figure 11, which shows results from 60° latitude in the experiments where chlorine releases were halted in the year 2000 (scenario B). In the scenario A and C cases, the rate of increase is not only larger than the globally averaged column; it also starts faster. The ozone minimum is reached after 5 years, while the corresponding time for the globally averaged column was shown to be 10-15 years (Figure 10). The local behavior of ozone at 60° northern latitude at the 43 km level is similar to the behavior of total ozone. Minimum ozone is obtained 5-6 years after the emissions are ceased, and ozone recovery is fast thereafter. If emissions are reduced by 7% per year instead of being completely stopped, the period of decreasing ozone is prolonged to 13 years, according to our results.

NONLINEAR OZONE REDUCTIONS AT VERY HIGH CHLORINE LEVELS

Since Cicerone, Walters, and Liu (1983) reported a pronounced nonlinear relationship between ozone reductions and increases in stratospheric chlorine, this relation has been subject to extensive studies. Cicerone, Walters, and Liu (1983) found a more rapid growth in ozone reductions than in stratospheric

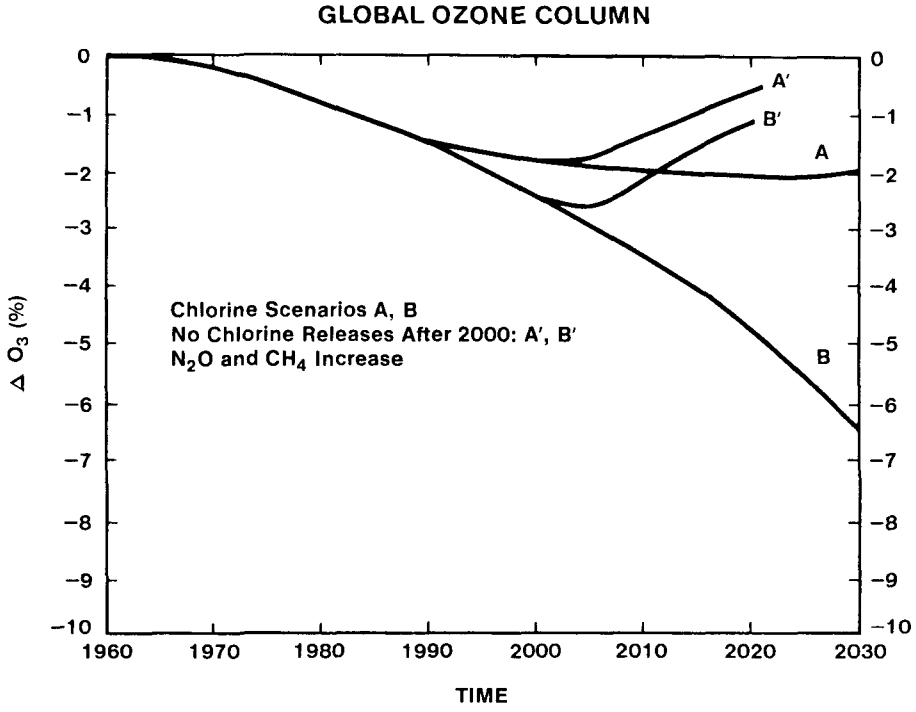


Figure 10. As Figure 5 for the chlorine scenarios A and B. Also included is the change in ozone column after a cease in the chlorine emissions after the year 2000. Growth in N_2O and CH_4 is included.

chlorine for Cl_x mixing ratios up to about 10 ppb. Rather, McElroy, and Wofsy (1985); Herman and McQuillan (1985); and Isaksen and Stordal (1986) found the relationship to be almost linear in this Cl_x range. They found, however, a faster growth in ozone reductions than in Cl_x mixing ratios from the point where Cl_x becomes larger than the amount of stratospheric NO_y (total odd nitrogen). It was interesting to see if this situation occurred in the time-dependent experiments described in this paper. The values for Cl_x and NO_y in case C, the scenario with the largest chlorine emissions, are shown in Figure 12. The Cl_x concentration increases rapidly after the turn of the century and reaches 12 ppb in the year 2030, well below the predicted 25 ppb of NO_y. The point of accelerating ozone reductions is therefore reached much later than the year 2030 in all the calculations presented here. As discussed in Isaksen and Stordal (1986), there is still a considerable uncertainty in the modeled NO_y (as well as in NO_y measurements). The lower the values of NO_y, the earlier the accelerated ozone depletion will start. The NO_y results presented include an increase in N_2O of 0.25% per year, a growth rate that is somewhat uncertain. The accompanying increase in NO_y values is much slower than the growth in Cl_x. In the 50-year time period from 1980 to 2030 the stratospheric level of NO_y is projected to increase 16.5%.

To study the alterations in the ozone chemistry when Cl_x reaches the level of NO_y, we have run the scenario C case for an additional period of 50 years. The chlorine release rates for this period are also contained in Table 1. The yearly growth in emissions for CF_2Cl_2 and $CFCl_3$ are assured to decrease from about 2% in the year 2030 to less than 1% 50 years later. Since

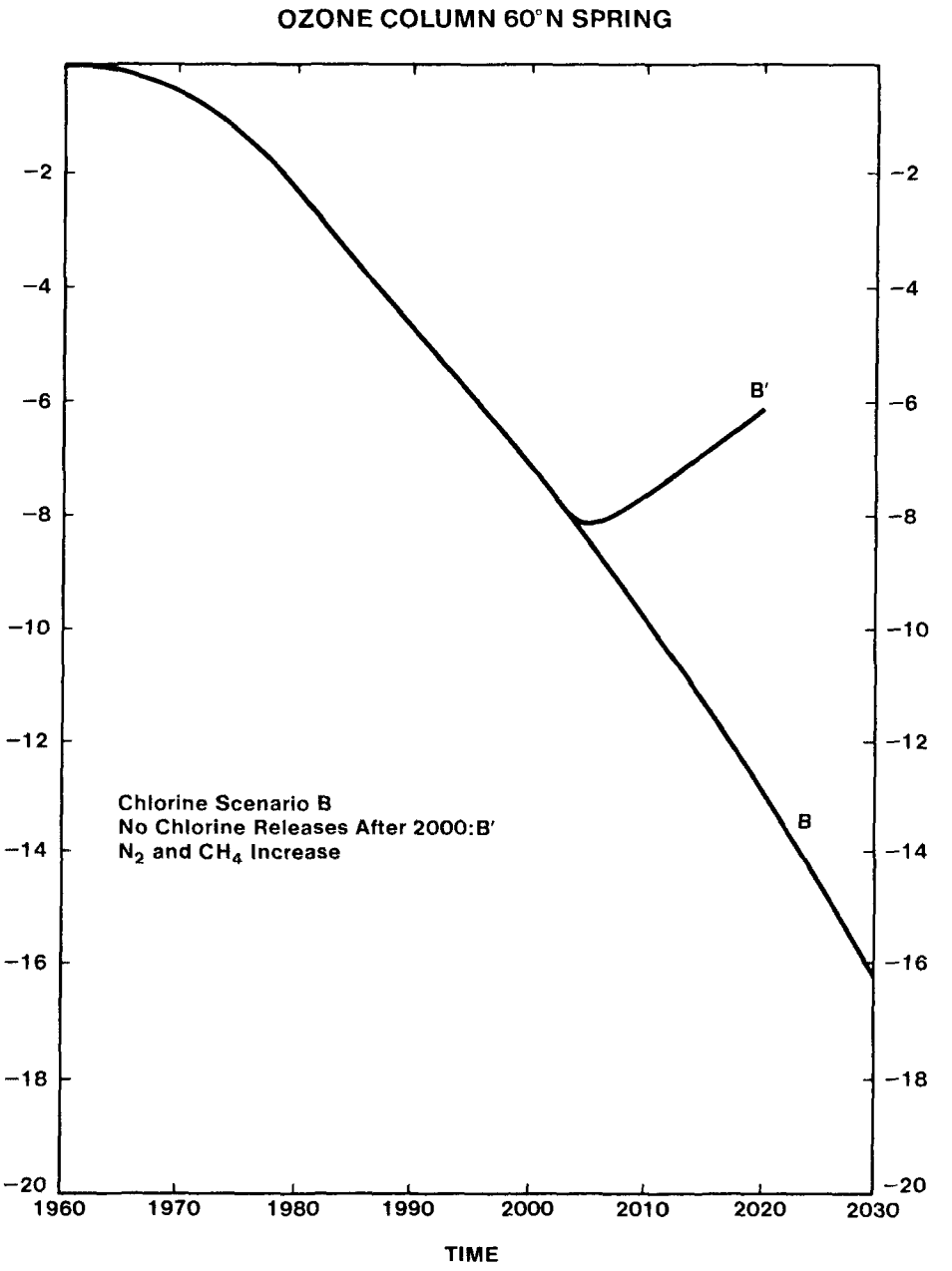


Figure 11. As Figure 10, but for the ozone column at 60° northern latitude during spring.

the predicted increases in CH_4 and N_2O are based on currently observed trends, we find their scenarios through the middle of the next century to be highly uncertain. We have therefore assumed constant surface mixing ratios for CH_4 and N_2O in the period 2030-80. This assumption is also convenient for the current study since Cl_x levels then will exceed the level of NO_x earlier. With the adapted scenario, Cl_x catches up with NO_y between 2060 and 2070 and reaches 34 ppb in the year 2080.

Isaksen's and Stordal's (1986) steady-state experiments showed that for high levels of stratospheric chlorine, the most significant ozone reduction

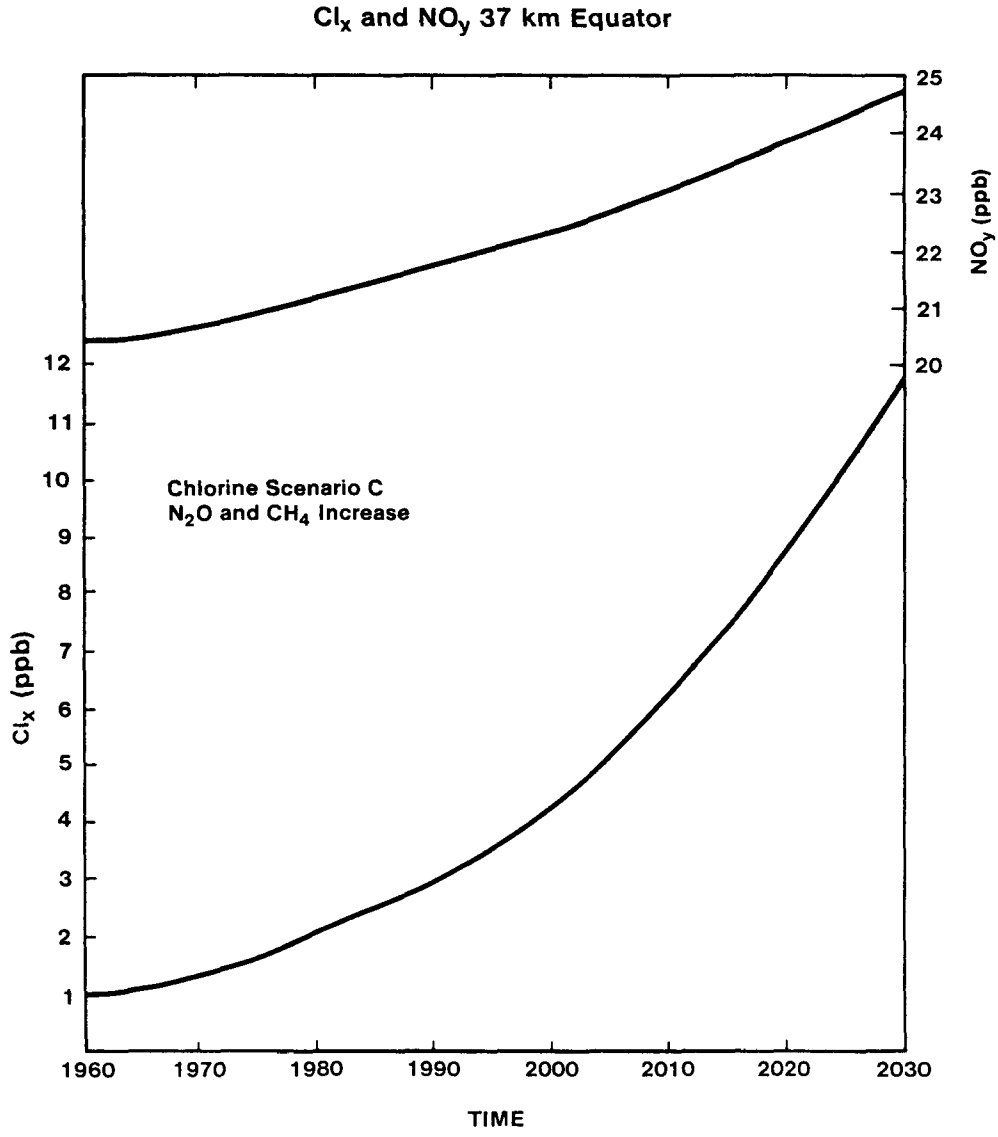
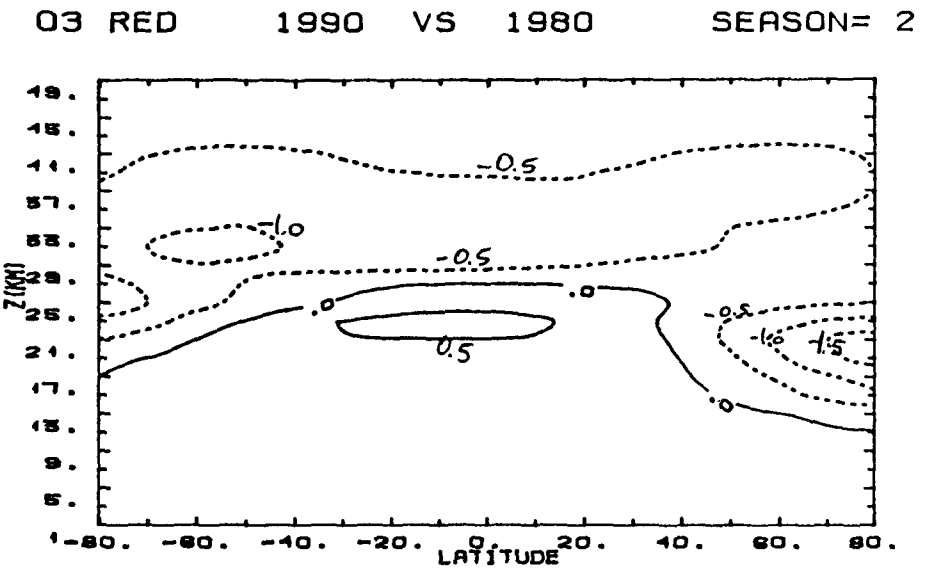
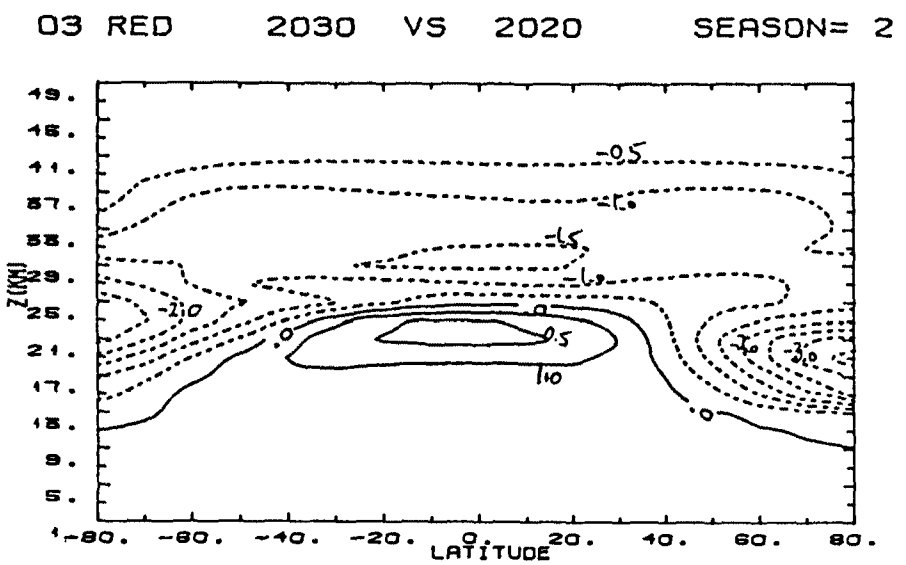


Figure 12. Maximum stratospheric levels of Cl_x and NO_y as function of time, in the chlorine scenario C case (see Table 1) with simultaneous increases in N_2 and CH_4.

will be in the lower stratosphere. Figures 13a-c illustrate that the time-dependent calculations confirm this behavior. The absolute changes in ozone concentration in three different 10-year periods are given as altitude-latitude contour plots. In the first period, 1980-90, the poleward and downward transport will result in maximum ozone depletions at high latitudes in the lower stratosphere. At middle and low latitudes, the largest depletions would be confined to the middle stratosphere. Forty years later, in the period 2020-30, the depletions in the middle and low latitudes would be intensified. The zero line separating the two regions would descend 2-3 km. As in the former period, the maximum decrease in the upper region (at middle and low latitudes) would be similar in magnitude to the maximum increase in the lower region. This is no longer the case in the period 2060-70 when the nonlinear growth in ozone depletions at low and middle latitudes would start. Maximum depletions would take place (as in Isaksen and Stordal 1986) in the 25 km region where the zero line was located 80 years earlier. The large projected ozone depletions are due to increase in stratospheric chlorine, which is shown to influence the loss rate of ozone increasingly, even in the lower stratosphere.





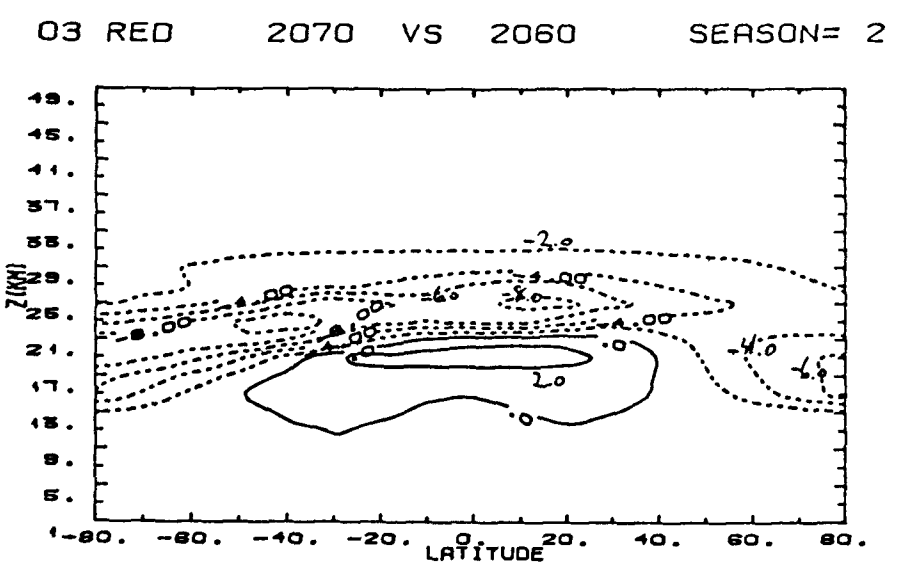


Figure 13. Changes in ozone densities (10^{11} molec cm^{-3}) as a function of altitude and latitude in the experiment discussed in the section on the response in ozone to future regulations in chlorine releases. The changes are given for the following 10-year intervals: 1980-90, 2020-30, and 2060-70.

We now focus on the rather dramatic changes in the chemistry of the lower stratosphere that are assumed to take place by the year 2080 when the stratospheric chlorine level becomes very large. Other chlorine reactions than reaction R7 below must then be considered. Wuebbles and Chang (1981) listed four different chlorine cycles resulting in O_x destruction (the number in brackets to the left-hand side of each equation represents the number of O_x molecules lost in the reaction, as described in the section titled Trend in Ozone for the Period 1970-80).

Cycle 1

(2)	$ClO + O$	$\rightarrow$	$Cl + O_2$		R7
(0)	$Cl + O_3$	$\rightarrow$	$ClO + O_2$		R8
Net:	$O + O_3$	$\rightarrow$	$2\ O_2$		

Cycle 2

(0)	$Cl + O_3$	$\rightarrow$	$ClO + O_2$		R8
(0)	$NO + O_3$	$\rightarrow$	$NO_2 + O_2$		R9
(0)	$ClO + NO_2 + M$	$\rightarrow$	$ClONO + M$		R10
(1)	$ClONO + hu$	$\rightarrow$	$Cl + NO_3$		R11
(1)	$NO_3 + hu$	$\rightarrow$	$NO + O_2$		R12
Net:	$2\ O_3$	$\rightarrow$	$3\ O_2$		

The dissociation of NO_3 has an alternative pathway to reaction (R12). Only the fraction of the dissociation forming NO (1/9, see NASA/JPL 1985) leads to O_x destruction. The net loss term for cycle 2 is then 2/9 J_{11} $ClONO_2$ since the $ClONO_2$ dissociation is the rate-limiting step (see, e.g., Wuebbles and Chan 1981; Cicerone, Walters, and Liu 1983).

Cycle 3

(0)	$Cl + O_3$	$\rightarrow$	$ClO + O_2$		R8
(0)	$ClO + NO$	$\rightarrow$	$Cl + NO_2$		R13
(2)	$NO_2 + O$	$\rightarrow$	$NO + O_2$		R6
Net:	$O + O_3$	$\rightarrow$	$2\ O_2$		

Cycle 4

(0)	$Cl + O_3$	$\rightarrow$	$ClO + O_2$		R8
(0)	$ClO + HO_2$	$\rightarrow$	$OHCl + O_2$		R14
(1)	$OHCl + hu$	$\rightarrow$	$OH + Cl$		R15
(1)	$OH + O_3$	$\rightarrow$	$HO_2 + O_2$		R2
Net:	$2\ O_3$	$\rightarrow$	$3\ O_2$		

At very high chlorine levels, OHCl dissociation (R15) becomes faster than the rate of the reaction $OH+O_3$ (R2). Another reaction is then converting OH to HO_2, namely OH+ClO, constituting a 5 O_x loss cycle:

Cycle 5

	$Cl + O_3$	→	$ClO + O$		R8
	$ClO + HO_2$	→	$OHCL + O_2$		R14
(1)	$OHCl + hu$	→	$OH + Cl$		R15
(1)	$OH + ClO$	→	$HO_2 + Cl$		R16
	$Cl + O_3$	→	$ClO + O_2$		R8
Net:	$2\ O_3$	→	$3\ O_2$		

Cycle 1 is the only pure chlorine cycle, while the four remaining cycles involve nitrogen (2 and 3) and hydrogen (4 and 5) compounds. As noted in Wuebbles and Chang (1981), the distribution of the ozone loss between the individual families is then not obvious. We have taken the following approach in this study:

Cycle 3 has the O_x loss reaction (R6) in common with the pure nitrogen catalytic cycle:

$NO_2 + O$	→	$NO + O_2$	R6
$NO + O_3$	→	$NO_2 + O_2$	R17

We distribute the O_x loss between the two cycles so that T17/(T1+T17) is attributed to the pure nitrogen chain and the remaining T13/(T13+T10) to chlorine cycle (3). Here T_n represents the rate K_nXY of reaction R_n with X and Y as reactants.

The rate-limiting process in cycle r is reaction (R16). The loss rate of cycle (5) is therefore set to the rate of R16 times two, since two O_x are lost in each cycling. The OHCl dissociation (R15) is common for cycles 4 and 5. The part of the rate of this reaction that exceeds the rate of R16 is attributed to cycle (4). This cycle has reaction R2 common with the pure hydrogen loss chain

$OH + O_3$	→	$HO_2 + O_2$	R2
$HO_2 + O_3$	→	$OH + 2\ O_2$	R3

Only the part of the rate of R2 that has not been involved in the chlorine cycles (4) and (5) is attributed to the pure hydrogen caused O_x loss.

Figures 14a-f show the fraction of the O_x loss attributed to the various chlorine cycles in the year 2080. Altitude-latitude cross sections are given for the season March-May. In the region of chemical control, chlorine cycles account for at least 80% of the total loss. The contribution of the pure hydrogen cycle is reduced to less than 10% except around the stratosphere where a 10% influence remains. The influence of the pure nitrogen cycle as well as the oxygen cycle is also less than 10%. Chlorine cycle (1) is dominating, even in the lower stratosphere. At low latitudes, this cycle

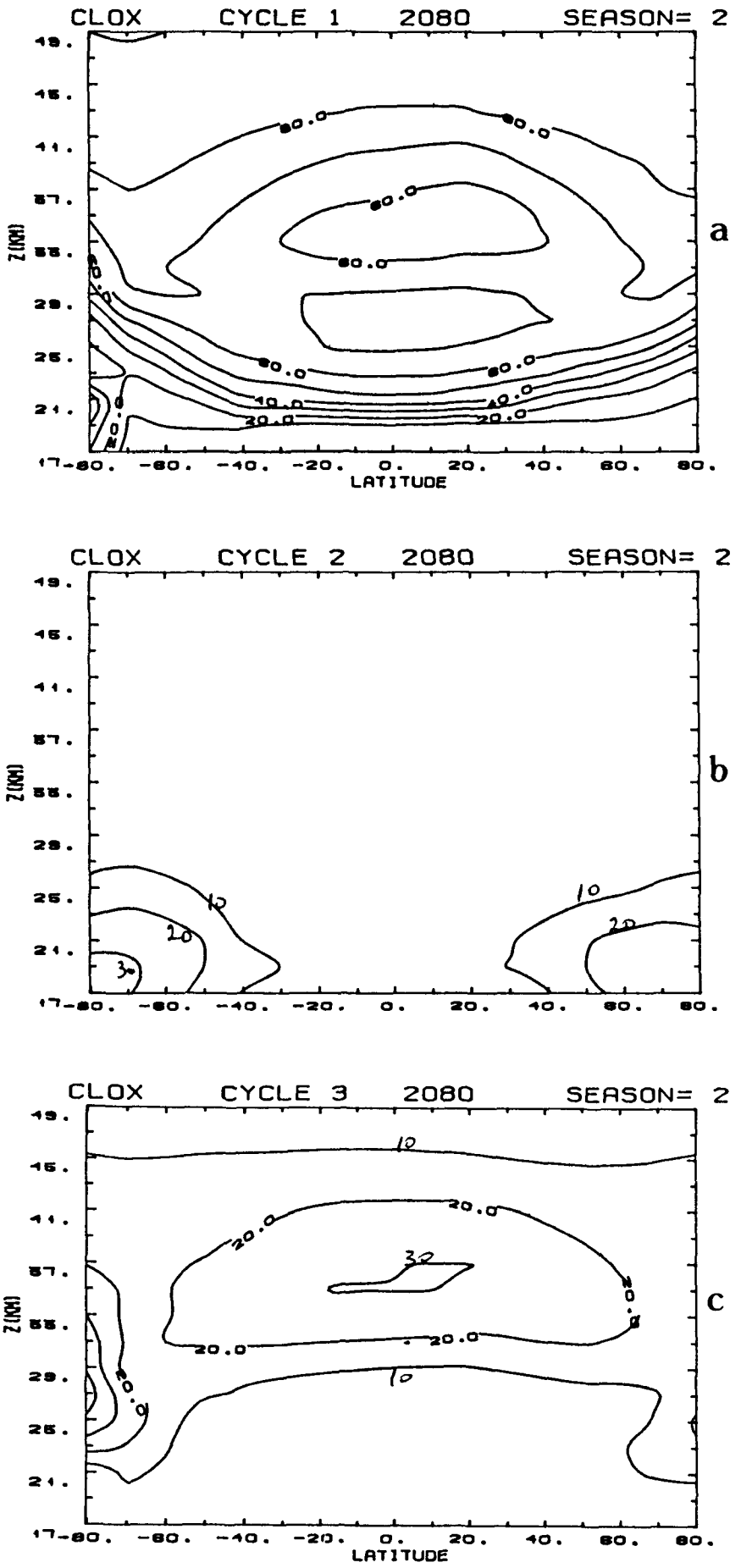
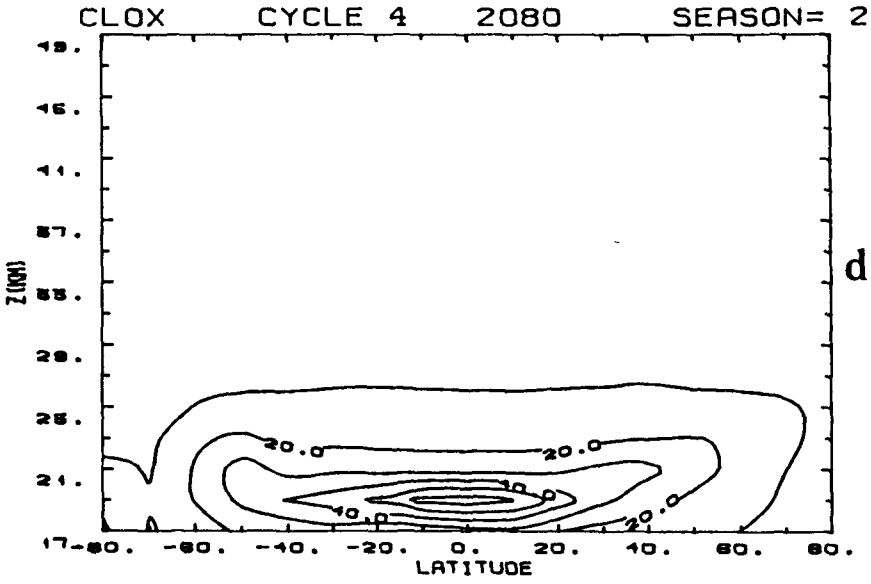
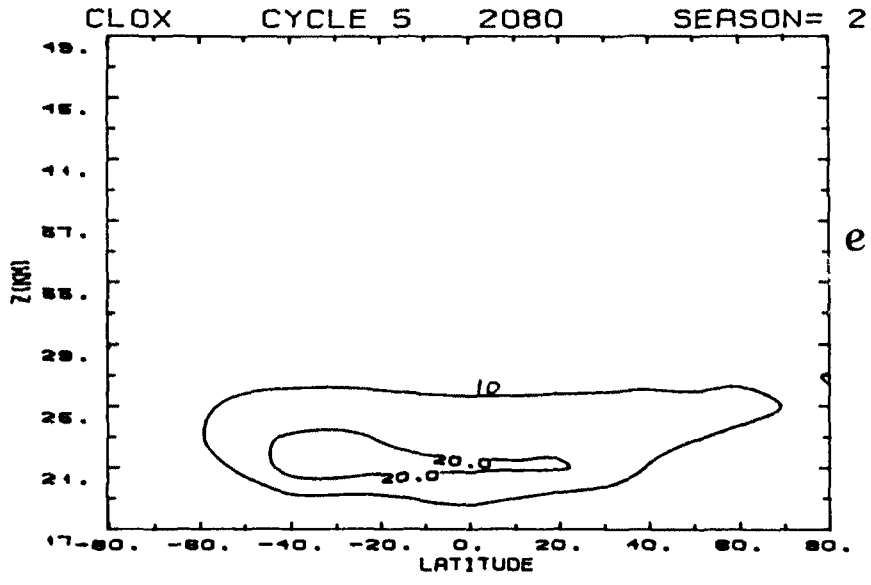


Figure 14. Percentage ozone loss rates due to ClO_x cycles (see text, the section on nonlinear ozone reductions at very high chlorine levels). Altitude-latitude contours are given for near equinox conditions in the year 2080 of the experiment discussed in the section on the response in ozone to future regulations in chlorine releases.





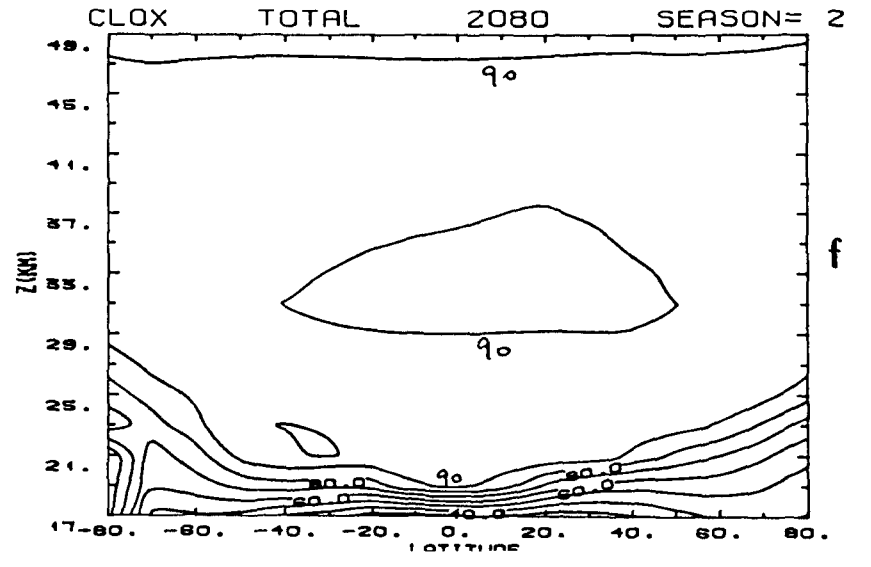


Figure 14 (Cont.)

stands for more than 60% of the total loss at the 25 km level. In the middle stratosphere cycle (3) is the second largest depletion cycle, attaining a maximum of more than 30%. Below the 25 km level the two cycles involving OHCl, cycles (4) and (5), gradually increase their influence. Each of these cycles contributes to the O_x loss with about 10%-20% in the transition region. The chlorine cycle (2) involving chlorine nitrate is effective only at very low altitudes at high altitudes where contributions of 10%-20% are obtained.

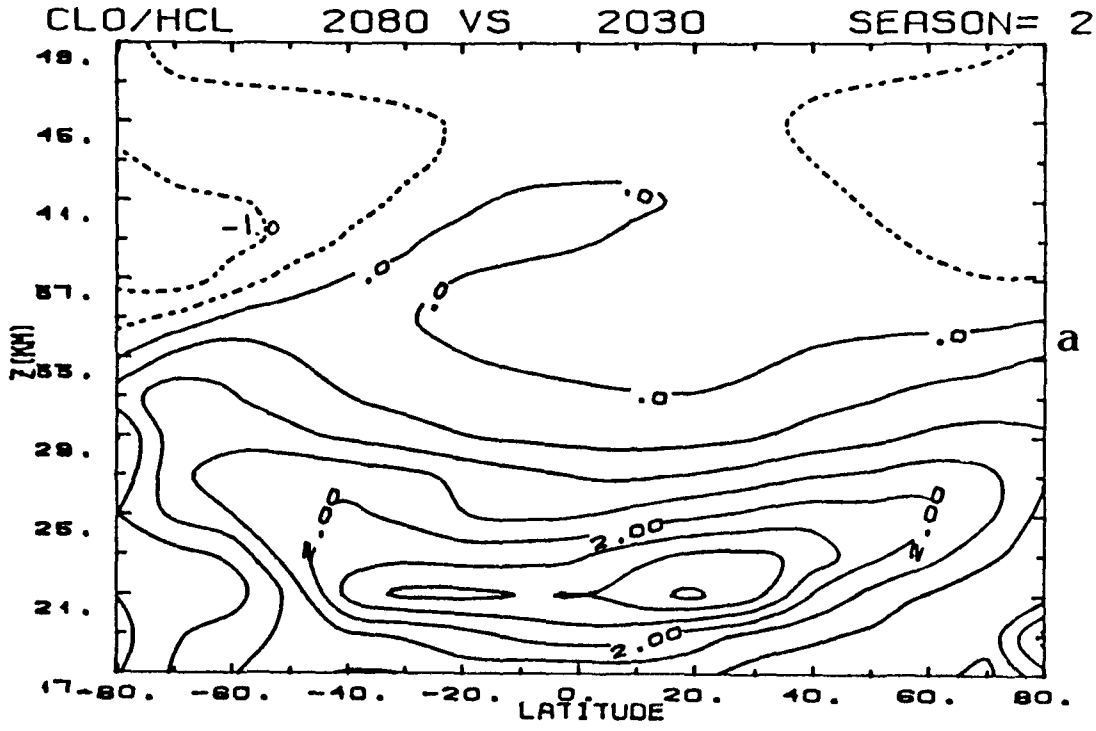
Since the chemistry of O_x in the year 2080 is dominated by the chlorine cycles, as demonstrated in Figures 15a-d, the explanation to the accelerated growth in ozone depletion must be sought in the chlorine chemistry. At all altitudes above the 30 km level more than half of the ozone has vanished in the year 2080, leading to a slower growth in ozone depletions there. Accelerated depletion of the total column can only take place due to the highly nonlinear increase in ozone reductions in the lower stratosphere, which was demonstrated in Figures 13a-c.

As discussed in Isaksen an Stordal (1986), the explanation for the accelerated chlorine influence can be found in the changes in the balance between ozone-depleting components and passive reservoirs in the chlorine chemistry in the lower stratosphere. The calculations show that HCl has effectively been converted mainly to ClO but also $ClONO_2$ in the region in the period 2030-80.

The explanation for the increase in the fraction of ClO must be sought in changes in components determining the balance between the chlorine components. Figures 15a-d show the change in the period 2030-80 in some key components as well as in the ratio between ClO and HCl. The increase in the ratio ClO/HCl is large in the lower stratosphere. At the 25 km level at low latitudes this ratio has increased by a factor 3-4 in the 50-year period in question. The ratio can be expressed as a product of the ratios ClO/Cl and Cl/HCl. The first of these ratios, ClO/Cl, increases by a factor of about 2 since the NO concentrations drop (Figure 15b), lowering the rate of reaction R13. The Cl/HCl ratio increases by a factor 1.5-2 in the lower stratosphere at low latitudes, since CH_4 decreases (Figure 15c) and OH increases (Figure 15d). Both favor an increase in the decreases since OH increases and since the reaction $Cl + CH_4 \rightarrow HCl + CH_3$ (R18) becomes a significant loss reaction for CH_4 in the upper stratosphere. OH increases due to lowered levels of HNO_3 and HO_2NO_2 (Prater et al. 1985) as well as an efficient transformation from HO_2 via HOCl (see detailed discussion in Isaksen and Stordal 1986).

The time-dependent experiments described here confirm the point made by Isaksen and Stordal (1986) that accelerated ozone depletion at high chlorine levels occurs as a result of the fractional ClO increase. OHCl and to some extent $ClONO_2$ contribute to the nonlinearity.

According to the present understanding of the chemistry of the stratosphere (NAS/JPL 1986), the transformation of the active components Cl and ClO to the main reservoir HCl takes place through Cl reactions. At high chlorine levels, when the Cl-ClO balance is shifted towards the latter component, the loss mechanisms for Cl+ClO are less efficient. Isaksen and Stordal (1986) demonstrated, however, that only small yields of reactions like ClO+OH and OHCl+hu for pathways leading to HCl formation could decrease the nonlinear ozone depletion significantly.



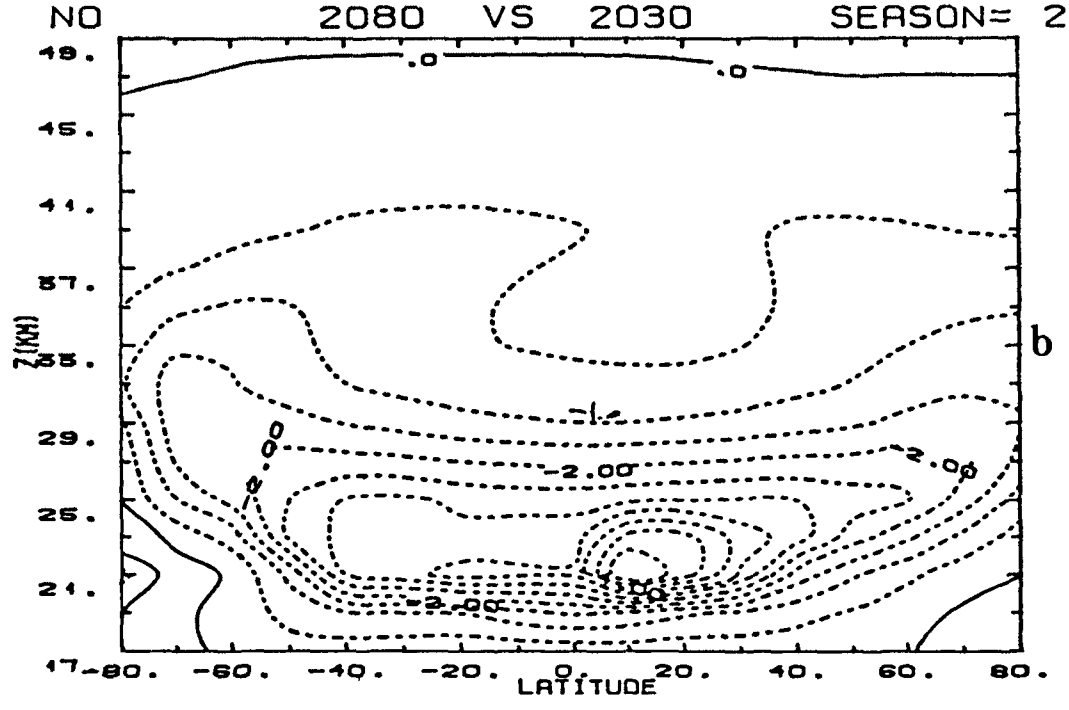
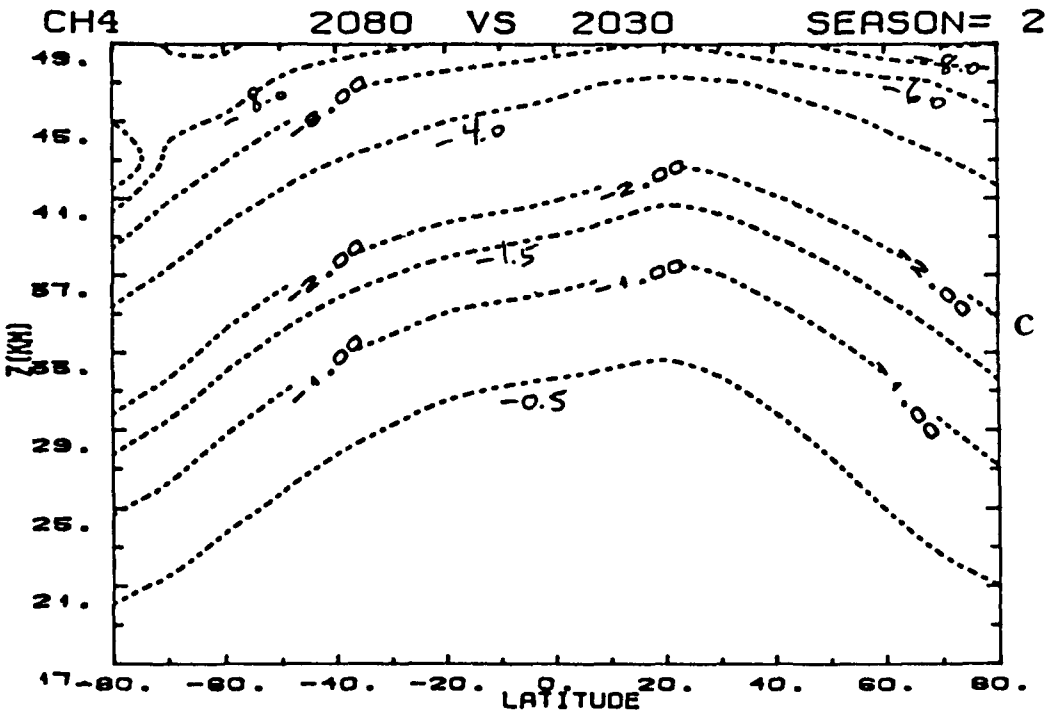


Figure 15. Changes in ratios and components in the period 2030-80 in the experiment considered in the section on nonlinear ozone reductions at very high chlorine levels. Altitude-latitudes cross sections for near equinox conditions are given for the quantities $\log_2 (H_{2080}/H_{2030})$ where H represents, firstly, the ratio a) ClO/HCl, and secondly, the mixing ratios of b) NO, c) CH_4, and d) OH.



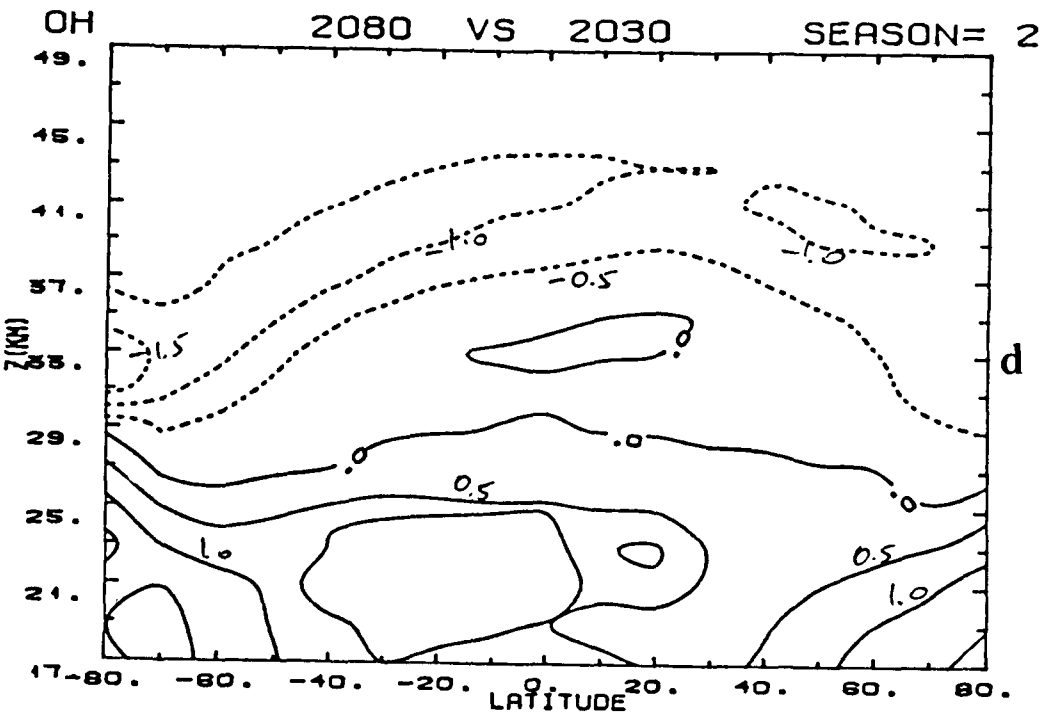


Figure 15 (Cont.)

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The Ultraviolet Radiation Environment of the Biosphere

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ABSTRACT

The flux of biologically significant ultraviolet radiation that reaches the surface of the earth varies markedly with season and latitude. A comparison of computed UV-B (280 to 320 nm) and UV-A (320 to 400 nm) surface fluxes shows the greatest latitudinal and temporal gradients at the shorter wavelengths where atmospheric ozone is an efficient absorber. Calculations performed for four cities in the United States define the respective roles of the solar zenith angle and the column ozone amount in determining the biologically damaging flux of solar radiation incident on the biosphere. These variables, together with surface elevation, combine to produce significantly different radiation environments in the cities analyzed.

INTRODUCTION

The amount of solar ultraviolet radiation that reaches the biosphere is controlled by several factors of which the best known is the amount of atmospheric ozone. This paper defines the major variables required to predict the flux of biologically relevant solar radiation at the surface of the earth and shows how they combine to produce large latitudinal and seasonal variations in the energy received at the ground. The sun emits electromagnetic radiation over a broad range of wavelengths, of which the human eye responds to the region from approximately 400 to 700 nm. This work focuses on shorter wavelengths located in the near ultraviolet. The region from 320 to 400 nm is termed the UV-A, while the UV-B lies shortward of this, from 280 to 320 nm. Absorption of solar radiation by ozone is significant primarily at UV-B wavelengths.

One can think of the atmosphere as a filter located between the sun and the earth's surface. The transmission of this filter for solar radiation is a very sensitive function of wavelength, geographic location, and time of year. Figure 1 presents a reference solar spectrum both at the top of the

atmosphere and at the earth's surface for conditions typical of afternoon illumination at a middle latitude site. The extraterrestrial flux represents a combination of recent rocket and satellite measurements. The total energy flux incident on the atmosphere over the entire UV-B and UV-A combined is approximately 109 watts per square meter. This is similar to the power of a standard 100 watt light bulb being directed onto each square meter of area at the top of the atmosphere.

The lower curve in Figure 1 illustrates the solar UV-B and UV-A energy flux reaching the ground for clear sky conditions. The solar zenith angle in this calculation is 60°. (The solar zenith angle is the angle between the point directly overhead and the sun. A solar zenith angle of 90° means that the sun is on the horizon.) The most obvious feature in Figure 1 is the very sharp decline in energy flux as one moves toward shorter wavelengths from the UV-A into the UV-B. This is the well-known "ozone cutoff" in which the flux at the ground drops to negligible levels over a wavelength range of a few nanometers. For most purposes one does not consider radiation at wavelengths less than 295 to 300 nm as reaching the surface of the earth. However, the surface flux in the region of the rapid dropoff is very sensitive to the atmospheric ozone amount.

At wavelengths longer than 320 nm, absorption by ozone becomes weak. Yet Figure 1 shows that the radiation flux reaching the ground is still much less than is incident at the top of the atmosphere. This attenuation arises from scattering by atmospheric molecules, mainly O_2 and N_2. Some of the incoming solar radiation is backscattered and exits the earth's atmosphere into space. This constitutes the albedo of the planet in the ultraviolet. Hence, even in the absence of an ozone layer the earth's surface would be partially shielded from the sun's ultraviolet emissions. However, in such a circumstance the lethal radiation in the UV-B would be vastly greater than the values to which life is now adapted.

Photobiological responses are sensitive functions of the wavelength of incident light. This wavelength dependence is described mathematically by a biological "action spectrum," which is simply a quantitative way of saying that some wavelengths are more efficient than others at causing a specific type of photobiological response. Figure 2 is a sample action spectrum for a type of radiation damage to the DNA molecule (Setlow 1974). This figure shows that biological sensitivity is greater at the wavelengths where the solar radiation reaching the ground is smaller and vice-versa. For biological applications the relevant quantity is the product of an action spectrum and the solar flux at the ground added over all wavelengths (mathematically, the "convolution" of the action spectrum with the solar flux). This provides a single number (rather than a series of numbers at many wavelengths) that depends on the biological process under study and varies with the radiative transfer properties of the earth's atmosphere. A combination of the values in Figures 1 and 2 implies that radiation at wavelengths in the 300 to 315 nm region is overwhelmingly the most important in damaging the DNA molecule. This is a region where atmospheric ozone exerts a major influence on the solar flux reaching the ground.

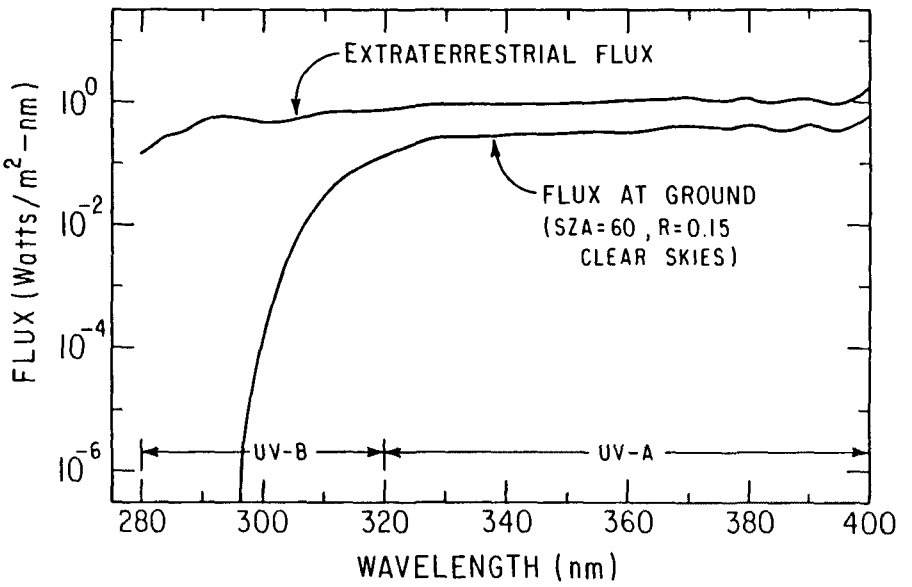

Figure 1. Reference solar ultraviolet spectrum incident on the top of the atmosphere (extraterrestrial flux) and at the ground for typical afternoon conditions and a middle latitude location. The calculations assume a solar zenith angle (SZA) of 60°, a ground albedo (R) of 15%, and clear skies.

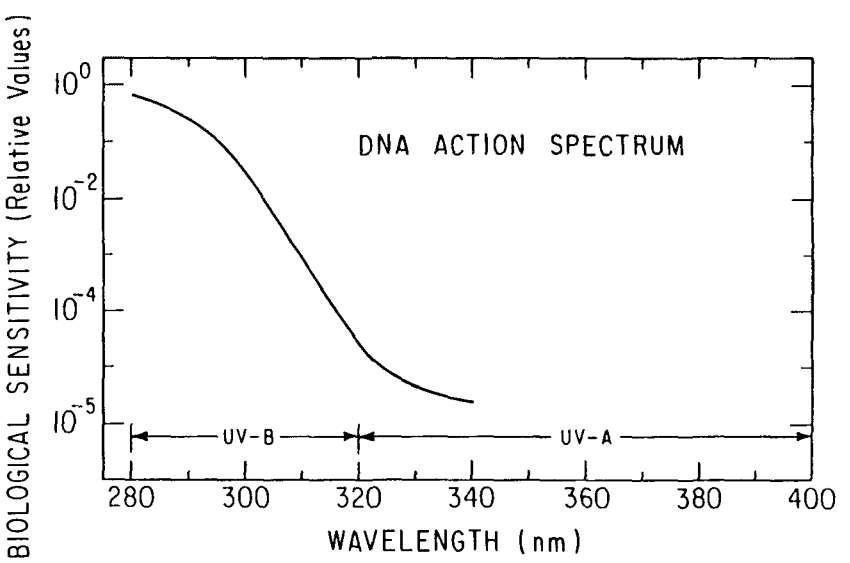

Figure 2. Action spectrum for damage to the DNA molecule. The vertical scale is a relative measure of biological sensitivity to radiation at each wavelength.

The Latitudinal Distribution of Radiation

Figure 3 presents the global distribution of UV-B radiation at the surface of the earth computed for clear sky conditions. Contours in the figure are in watts per square meter and appear as functions of latitude and month. All values refer to a local time of 10:00 A.M. and represent the sum of all radiation at wavelengths between 280 and 320 nm. The largest energy fluxes, four watts per square meter, exist in the tropics because the sun is almost directly overhead, and the atmospheric ozone amounts are relatively small. The large variation in radiation flux with latitude, especially during the winter season is illustrated in Figure 3. In the Northern Hemisphere during December and January, the flux decreases by a factor of ten between the equator and 50° latitude. If one considered a calculation in which the radiation at each UV-B wavelength is weighted by an action spectrum value, the gradients in latitude would be still more pronounced than those of Figure 3 because shorter wavelengths, where ozone absorbs most efficiently, would be relatively more important. During summer the latitudinal changes are much less pronounced than in winter, and one must move from the tropics to 60° to experience a factor of two decrease in radiation at the ground. Accompanying this latitudinal behavior are seasonal variations. In the tropics there is very little change in the 10:00 A.M. fluxes over the course of a year. At middle latitudes, however, the seasonal cycle can range between a factor of two and ten depending on location.

A calculation analogous to Figure 3 could be done for the UV-A spectral region. Although the contours would be similar in shape, the gradients would be much less pronounced because of the greatly reduced absorption by ozone at wavelengths longward of 320 nm. Figure 4 illustrates this behavior with the contours of the ratio of the UV-B and UV-A fluxes. Clearly, the UV-B flux is much smaller than the UV-A, with the ratios ranging between 2 and 7.5 percent. The most significant information in Figure 4 is the differing latitudinal and seasonal gradients shown by the UV-B and UV-A. As one moves from the tropics to 60° latitude in winter, the UV-B shows a decrease, which is a factor of three to four greater than the UV-A, while in summer the relative variation is much less than a factor of two.

Radiation Received by Selected Cities

For many medical applications the relevant quantity is the radiation received at a specific locality weighted by the action spectrum for the particular photobiological process under study. The calculations that follow use the DNA action spectrum of Figure 2, and therefore one must not view the results as applicable to all cases of biological interest. Figure 5 presents the annual cycle of "biologically damaging" flux (flux at the ground convolved with the DNA action spectrum) for four cities in the United States. The calculations refer to local noon for clear sky conditions, and results appear in relative units. Miami represents a low latitude site (25.8° N), and consistent with the global contours of the previous section, the radiation flux here is significantly larger than that received by the more northerly locations. Boston is the highest latitude site in Figure 5 (42.3° N). A comparison of Miami and Boston reveals a factor of 1.5 difference in damaging radiation during July, and a factor of 8.5 in winter.

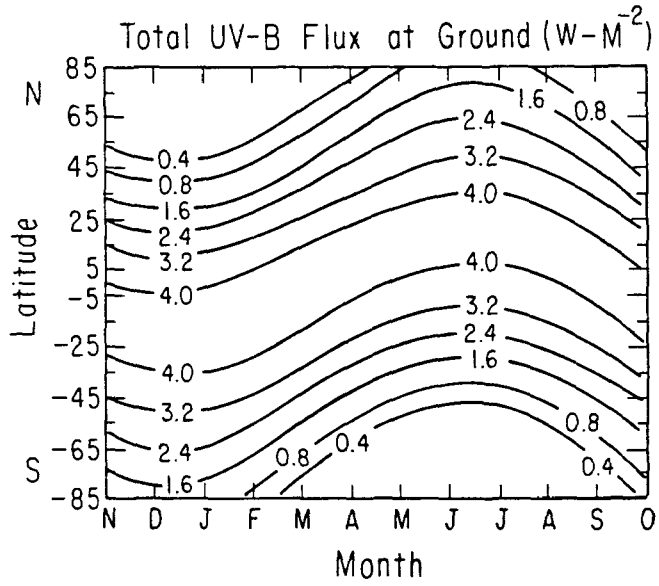

Figure 3. The latitudinal and monthly distribution of UV-B radiation at the ground computed for clear sky conditions and a local time of 10:00 A.M. Contour values, in watts per square meter, include all wave lengths between 280 and 320nm.

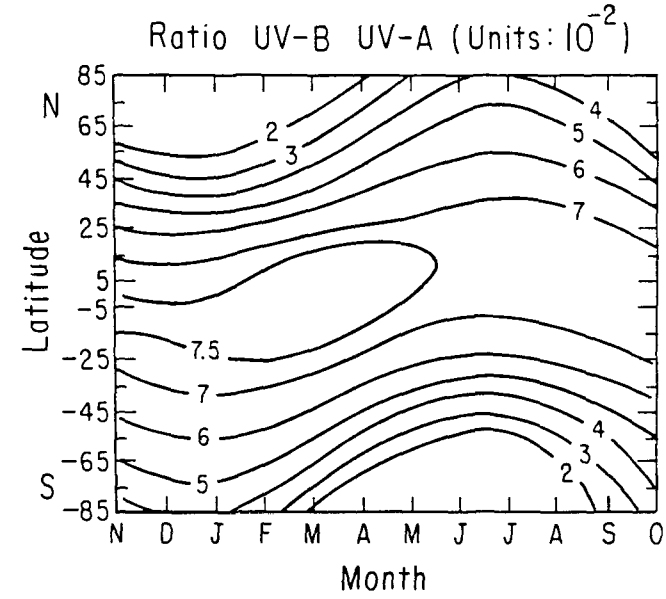

Figure 4. The ratio of solar energy flux in the UV-B (280-320 nm) to that in the UV-A (320-400 nm) as a function of latitude and month. Values refer to radiation reaching the ground for 10.00 A.M. local time and clear sky conditions. Contours are in percent (7.5 means that the UV-B energy is 7.5 of that in the UV-A).

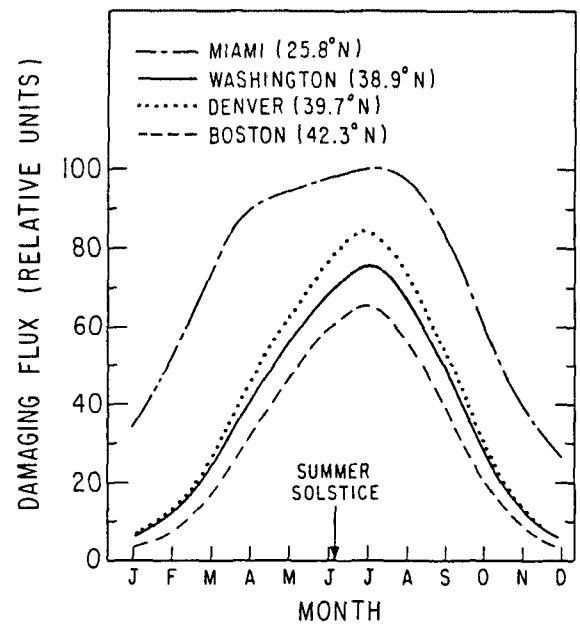

Figure 5. Biologically damaging solar flux received at the ground computed for four cities in the United States during each month of the year. Results refer to clear skies at local noon. The damaging flux is the convolution of the solar flux at the ground with the DNA action spectrum. Values are in relative units, normalized to a maximum of 100.

Denver (39.7° N) and Washington, D.C. (38.9° N) are at similar latitudes, although based solely on their 0.8° separation one would expect slightly larger fluxes in Washington (for clear skies and the same local times). Figure 5 shows that this is not the case, and in July the Denver radiation level is approximately 12 percent greater than that in Washington. This offset shrinks to 9 to 10 percent in January. The elevations of the two metropolitan areas are the source of the computed differences. The surface atmospheric pressure at Denver is approximately 85 percent of that for Washington, D.C. This means that over Denver there is less atmospheric mass available to scatter incoming solar radiation back to space than for elevations closer to sea level. The result is a greater radiation flux at the ground. In summer for clear sky noon conditions, a one kilometer increase in elevation is accompanied by roughly a 7 to 8 percent increase in biologically damaging flux. In winter the computed change is closer to 6 percent per kilometer, although the absolute radiation levels are vastly smaller here than in summer.

Based on the annual cycle in solar zenith angle, one would predict maximum damaging radiation levels at the summer solstice (June 21). Yet, inspection of Figure 5 reveals that the peaks lie closer to mid-July. (Note that the tick marks on the horizontal scale of Figure 5 refer to the centers of each month.) Figures 6 and 7 allow one to interpret the annual cycles in radiation. First, Figure 6 illustrates the noon solar zenith angles for the four cities in each month, where the minimum values obviously occur at the summer solstice. The annual cycle in radiation flux at the ground clearly varies inversely with the solar zenith angle. This dependence arises from the varying slant path taken by the sunlight through the absorbing and scattering atmosphere during different times of the year. Both absorption by ozone and scattering by atmospheric molecules act to decrease the flux reaching the ground as the radiation path through the atmosphere increases (i.e., as the solar zenith angle increases).

The shift in time between minimum solar zenith angle and maximum radiation flux arises from the annual cycle in atmospheric ozone depicted for each city in Figure 7. Note that the total ozone in a vertical column of the atmosphere is not simply related to the solar zenith angle. Although ozone is produced by the action of ultraviolet sunlight on O_2 molecules in the upper atmosphere, much of the ozone that exists in a vertical column has drifted downward from higher altitudes. At altitudes below thirty kilometers, where most of the ozone resides, the lifetime before chemical conversion back to O_2 is long. The abundance here is controlled by atmospheric transport processes that carry ozone from low to high latitudes during the winter, leading to the mid-latitude maxima of Figure 7 in February and March. The rapid decrease in ozone taking place between 35° and 45°N during late spring and early summer effectively suppresses a radiation maximum in the time immediately before summer solstice, and promotes a maximum shortly after solstice. This is the mechanism that shifts the maximum radiation fluxes of Figure 5 into July. Note also that the behavior of total ozone over Miami in Figure 7 is more representative of a tropical than a mid-latitude site. The relatively small ozone amount combined with an annual behavior different from that at higher latitudes leads to a seasonal cycle in surface ultraviolet radiation with a shape distinct from that at more northerly locations.

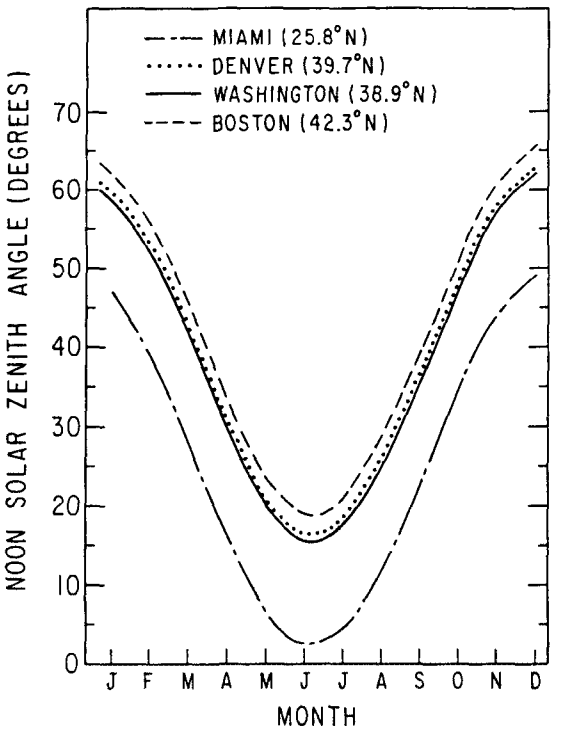

Figure 6. Variation of the noon solar zenith angle during one year computed for four cities.

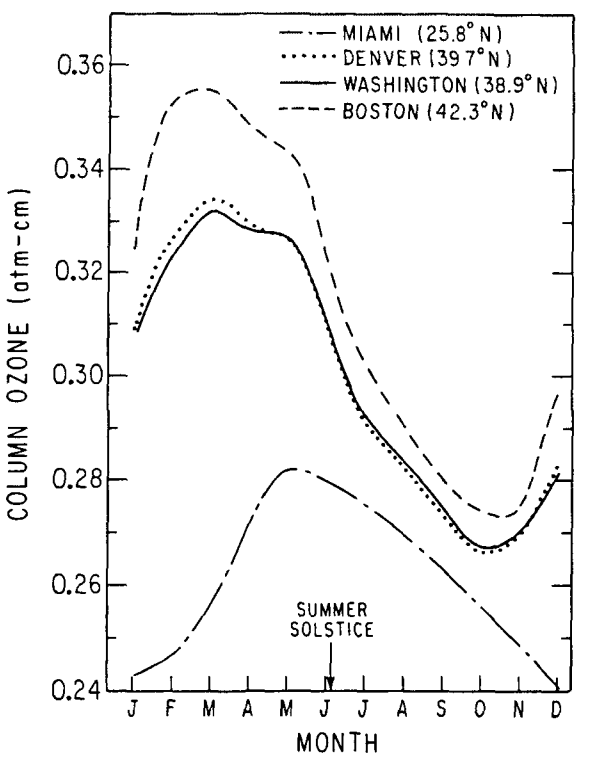

Figure 7. Variation in total column ozone during one year for four cities (in centimeters at atmospheric pressure). Values are based on measurements made by the Nimbus 7 Solar Backscatter Ultraviolet Spectral Radiometer.

CONCLUSIONS

We can conclude from this analysis that: (a) the gross shape of the annual cycle in biologically damaging radiation at a given location is determined by the variation in solar zenith angle; (b) the ozone amount influences details of the shape shown by the annual radiation cycle and is the major determinant of the absolute magnitude of the radiation flux for a given solar zenith angle; and (c) the biologically damaging radiation flux at latitudes between 35° and 45° varies by approximately an order of magnitude from winter to summer.

The availability of global scale ozone measurements and accurate information concerning the extraterrestrial solar irradiance permits more thorough studies of the ultraviolet radiation environment of the biosphere than have been possible in the past. However, a major deficiency of our results is the neglect of cloudcover and other forms of atmospheric turbidity. Data sets now exist that could provide valuable information on the reflectivity and transmission of clouds in the near ultraviolet. This information should be exploited both for applications in atmospheric science and photobiology. In addition, it is essential that a long-term measurement program be capable of providing unambiguous evidence of any changes in the global ozone amount.

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Health Effects of Ultraviolet Radiation

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SOURCES OF ULTRAVIOLET RADIATION

People are exposed to ultraviolet radiation from both natural sunlight and artificial sources; the most important source for humans is the sun. Virtually all of us are exposed to solar radiation at some time in our lives. In the United States an estimated eight million outdoor workers have occupational exposure to solar radiation. The sun is a complex source. Although we refer to "sunlight," solar radiation contains not only visible rays but also substantial portions of ultraviolet radiation--near, middle, and far infrared and other portions of the electromagnetic spectrum, including cosmic rays, microwaves, and radiowaves.

In this paper I present a general introduction to the health effects of ultraviolet radiation emphasizing photobiologic principles that are necessary to understand the significance of the work presented at this conference. Because many scientists have contributed to our knowledge of this field, my references are not exhaustive and generally direct readers to major reviews. Ultraviolet radiation, particularly its UV-B component, has major effects on the skin and eye. Other effects, including systemic effects have been claimed, but these are not discussed in this paper.

For convenience, we customarily divide the ultraviolet into three wavebands, UV-A, UV-B, and UV-C, whose properties are indicated in Table 1. This table is an oversimplification. The distinction between the wavebands is not sharp, and shorter UV-A rays can behave like UV-B. Interactions between the various wavebands of ultraviolet radiation and with other wavebands outside the ultraviolet may occur, particularly involving ultraviolet radiation and heat. However, this shorthand notation is convenient and serves to highlight UV-B, which is the focus of Volume 2.

Table 1. Wavelengths of Ultraviolet

Waveband		Properties
UV-A	320-400 nm	Not carcinogenic at usual exposure levels. Present in solar radiation at earth's surface. Responsible for most photosensitivity reactions.
UV-B	290-320 nm	Usually responsible for sunburn and skin cancer. Present in solar radiation at earth's surface.
UV-C	200-290 nm	Virtually totally removed by stratospheric ozone. Exposures occur only from artificial sources. Can cause erythema and skin cancer.

Artificial sources of ultraviolet radiation are varyingly rich in different regions of the ultraviolet. The total population exposed to these sources to any significant extent is much smaller than for solar radiation. The sources include welding arcs; germicidal lamps; sunlamps; therapeutic sources; environmental test chambers; printing, plastic, and paint curing and drying processes; ultraviolet lasers; plasma torches; and others. Relatively little is known about their long-term effects on exposed human groups.

Much of our knowledge about the effects of ultraviolet radiation comes from experiments on cellular systems, whole animals, and a relatively small number of experiments in human volunteers. The experimental ultraviolet sources used to develop this information were generally monochromators that deliver exposures to very narrow wavebands of ultraviolet, fluorescent sources including sunlamps (UV-C + UV-B + UV-A), germicidal lamps (predominantly 254 nm radiation), blacklights (predominantly UV-A), and xenon arc solar simulators (generally designed to simulate solar radiation in the UV-B but not in the visible or infrared). Most of our information about deoxyribonucleic acid (DNA) photochemistry has been generated using germicidal sources. There is an important discrepancy between solar radiation and the sources generally used in experimental studies. Furthermore, the spectral distribution of sunlight is not constant; it constantly varies within certain limits, depending on the latitude, altitude, time of year, time of day, and atmospheric conditions. Thus our observations about the effects of ultraviolet radiation in humans have been collected mainly through clinical case reports and epidemiologic studies related to exposure to ambient solar radiation that has a spectral distribution different from that of sources used for experimental studies.

TRANSMISSION OF UV THROUGH TISSUES

The ultraviolet radiation that reaches target cells in the body depends not only on the characteristics of the source and the radiation reaching the surface of the body, but also on the optical properties of the cells and tissues overlying the biological target. In these overlying tissues ultraviolet may be reflected, scattered, absorbed, or transmitted.

Figure 1 displays the seminal work of Boettner and Wolter (1962) measuring the total transmission of direct and scattered radiation through the tissues of the eye. The figure shows that very little ultraviolet shorter than 300 nm penetrates the cornea, and that very little radiation shorter than 400 nm penetrates deeper into the eye than the lens, whereas most of the visible radiation (400-780 nm) reaches the retina. To a large extent this explains why the effects of UV-C on the eye are virtually confined to the cornea, which explains why we are concerned about the possible effects of the longer ultraviolet on the lens. Interestingly, the rabbit eye often used for experimental studies shows transmission similar to the human eye (Geeraets and Berry 1968).

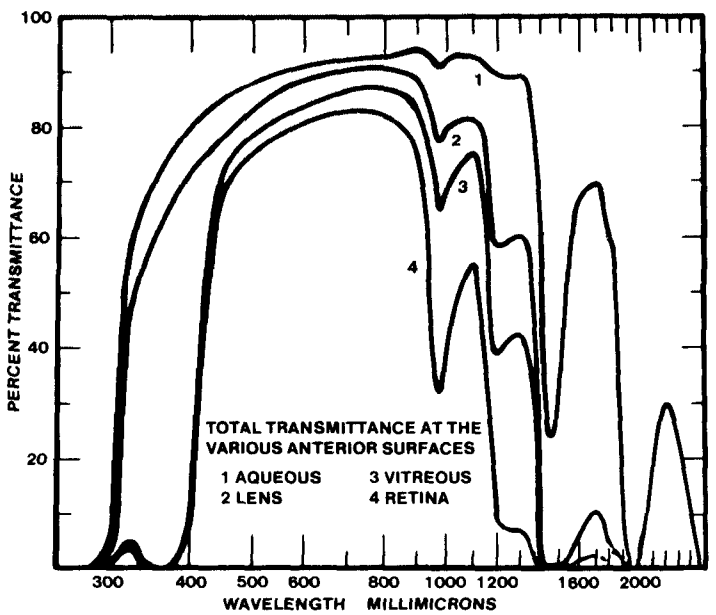

Figure 1. Total Transmittance at the Various Anterior Surfaces of Structures Within the Human Eye (from Boettner and Wolter 1986).

In the case of the skin, wavelengths from approximately 250 nm in the ultraviolet to approximately 3000 nm in the infrared penetrate the surface, but reach vastly different depths within the tissues (Anderson and Parrish 1982). The optical properties of skin are dynamic and vary with many factors including humidity, thickness of the skin layers, and the state of vasodilatation. Epidermal characteristics are of particular significance,

since the cells at greatest risk for ultraviolet carcinogenesis in people appear to be keratinocytes in the lowest layer and melanocytes within the lower few layers of the epidermis. An important variable in modulating individual susceptibility to ultraviolet is melanin pigmentation which provides maximum protection against wavelengths shorter than 1200 nm, including the entire ultraviolet range. Melanin is located primarily in the basal cell layer of the epidermis in pigment granules which can be seen to directly overlie the nuclei of many basal cells, like caps protecting the nucleus. It is very likely that this supranuclear, intracellular, distribution of melanin results in more protection against nuclear DNA damage than would random distribution of pigment in the skin.

SEQUENCE LEADING TO ULTRAVIOLET-INDUCED HEALTH EFFECTS

The sequence of events by which ultraviolet produces health effects is indicated in Table 2. Ultraviolet radiation must be absorbed to produce any response in tissues. This concept is central to photochemistry and photobiology. It was first proposed in 1818 by Grotthus and Draper and is known as "the first law of photochemistry." Further, as Frederick (this volume) describes, each absorbing molecule (chromophore) is capable of absorbing radiation only in specific wavelength ranges, a relationship described by its absorption spectrum. Each photon or quantum of radiation absorbed activates one molecule in the excitation step of a photochemical sequence.

Table 2. Sequence by Which Ultraviolet Radiation Produces a Health Effect

	Elapsed Time
Radiation	
↓	
Absorbed by Chromophore	
↓	
Excited State	10^{-9} - 10^{1} sec
↓	
Photochemical Reaction	10^{-3} - 10^{-7} sec
↓	
Biologic Response(s)	secs - years
↓	
Disease	

The electromagnetic energy absorbed in the chromophore is converted to chemical energy, resulting in molecular excitation and an excited electronic state. Some electronically excited states, notably triplet states, are much more long lived than others, and these are much more likely to result in photochemical changes. This electronic energy may be dissipated by heat or fluorescence, or in the formation of photoproducts either by rearrangement of the bonds within the excited molecule or by the interaction of the excited molecule with another molecule. The excited molecule can also initiate a photosensitized reaction, in which the molecule that absorbed the radiation transfers the energy to another molecule, which then forms products (Smith 1977).

Photochemical changes occur in many key biologic molecules and structures following ultraviolet irradiation. These include nucleic acids, proteins, lipids, steroids, melanin, urocanic acid, and others (Smith 1977; Harber and Bickers 1981). Damage occurs to the cell nucleus, cytoplasm, organelles, and membranes. Some (but not all) of the photochemical changes that immediately follow irradiation are fairly well characterized. However, the subsequent biologic changes are less understood.

Immediate biologic changes after exposure to ultraviolet include the release of chemical substances that mediate inflammation, inflammatory changes, numerous biochemical interactions involving reactive oxygen species, and immunologic changes including the suppression of certain immune response and various repair processes. But the precise sequence of these and other changes leading to the various health effects are not satisfactorily characterized in any instance. Clearly for some effects, such as carcinogenesis, these changes take place over many years.

ULTRAVIOLET DAMAGE TO DNA AND ITS REPAIR

Lesions in DNA, the essential genetic material in all living organisms, are of particular interest. The purine and pyrimidine rings of the nucleic acids, adenine, guanine, thymine, and cytosine, absorb maximally in the 245 to 280 nm range; and the major part of skin absorption of UV-C is by DNA rather than by protein or other molecules. Because of the extensive absorption of ultraviolet by DNA, the role of DNA damage in mutagenesis, and DNA's postulated role in carcinogenesis, considerable attention has been given to ultraviolet-induced DNA damage. Regardless of any long-term effects, ultraviolet damage to DNA produces substantial short-term effects including blocking the nucleic acid dependent processes of transcription and translation which are essential to cellular function and cell division. Above critical levels, this damage is irreversible and therefore leads to cell death.

Utraviolet-induced photolesions in DNA have been extensively reviewed (Rahn 1979; Saito et al. 1983). The best studied lesions are those where ultraviolet radiation causes a linkage of adjacent pyrimidines in DNA giving rise to cyclobutane-coupled pyrimidine adducts, often called pyrimidine dimers. Thymine-thymine, thymine-cytosine, cytosine-thymine, and cytosine-cytosine dimers are formed, and each exists in four stereo isomers. These lesions are normally repaired in humans and other species described below. In addition to cyclobutane-coupled pyrimidine dimers, ultraviolet induces other photoproducts in DNA. These include other dimers (single-bond-coupled-dipyrimidines, thyminyldihydrothymidine) and nondimer products including

thymine glycol, cytosine hydrate, DNA-DNA cross-links, and DNA-protein cross-links. Cells are usually able to repair at least some of these lesions, with important exceptions.

The repair of cyclobutane-coupled pyrimidine dimers in DNA has been given substantial attention in recent years. This repair seems to have biologic significance since the reversal of pyrimidine dimers at least partially restores colony-forming ability; transcriptional capacity; semiconservative DNA synthesis; and normal, low, mutagenesis rates in irradiated cells. Three types of repair have been defined: Excision repair, postreplication repair, and photoreactivation; other repair systems may exist.

In excision repair, a battery of enzymes act in a sequential manner to remove the dimer and subsequently to resynthesize undamaged DNA. This repair system is well developed in humans and is clearly deficient in the rare genetic disease xeroderma pigmentosum (XP), which is characterized by extreme sensitivity to the effects of ultraviolet, including an extraordinary sensitivity to ultraviolet-induced cancers.

The sequence of events in this repair has been shown to include the following: (a) pyrimidine dimer produced by ultraviolet distorts DNA molecule; (b) the backbone of the damaged DNA chain is broken by an enzyme, endonuclease; (c) a small region containing the thymine dimer is excised by another enzyme, exonuclease; (d) synthesis of new DNA strand, with correct bases corresponding to those on the remaining intact DNA strand; and (e) the two ends of the new strand are joined by a further set of enzymes designated as polynucleotide ligase.

Less is known about the other forms of DNA repair. Postreplication repair allows restoration of DNA synthesis without dimer removal. Gaps left in daughter DNA strands are filled in by de novo synthesis. Although this form of repair is not well understood, it does occur in humans (Lehmann 1975). Photoreactivation is a light-dependent process that requires a single enzyme and either UV-A or visible radiation. The original pyrimidines are reconstituted in situ without DNA strand breakage or resynthesis. Photoreactivation appears to occur in humans (Sutherland 1978), although its importance is not clear.

Recently scientists have found that not all genes are repaired with uniform ease (Bohr et al. 1985) and that certain chemical lesions (i.e., some forms of pyrimidine dimers) may be more resistant to repair than others (Lippke et al. 1981). As we understand these processes better, we will probably learn much about how cancer is actually induced by ultraviolet.

Humans with XP have a deficiency in DNA repair, clinical sun sensitivity, and excessive ultraviolet-induced skin cancers (Kraemer 1983). Cultured cells from patients with XP are unable to repair ultraviolet-damaged DNA. Cell fusion studies have demonstrated the existence of at least nine types of DNA repair defects, any of which may lead to the disease. Despite these studies, the specific responsible enzyme defect has not yet been identified for any form of XP. Most XP patients develop freckles very early in life and on continued exposure to sunlight develop abnormally 'aged' skin, eye abnormalities, and changes on the tip of the tongue. These changes are generally quite marked before the age of 10. Patients with XP have a greater than one

thousand increase in frequency of skin cancers including basal cell carcinomas, squamous cell carcinomas and melanomas. The predilection of XP patients to sun-induced diseases is so great that if a disease condition is seen in great excess in XP, it is taken as prima facie evidence that sun exposure causes the condition.

ACTION SPECTRUM AND BIOLOGICAL EFFECTIVENESS SPECTRA

For any biological response to ultraviolet radiation, there is an action spectrum which is defined as the relationship between the intensity of the response and the spectrum of wavelengths that incite the reaction. In practice, an action spectrum is most easily defined for acute and early effects of ultraviolet and is more difficult to determine for chronic and complex effects.

Figure 2 shows the action spectra curve developed by Cogan and Kinsey (1946) for keratitis (inflammation of the cornea of the eye) in the rabbit. The maximum sensitivity is at about 290 nm. The action spectrum for erythema of the skin has peaks at two wavelengths which are longer and shorter than those that produce keratitis. Neither of these spectra correspond exactly to the absorption spectra of either nucleic acids or proteins which are also shown in the figure.

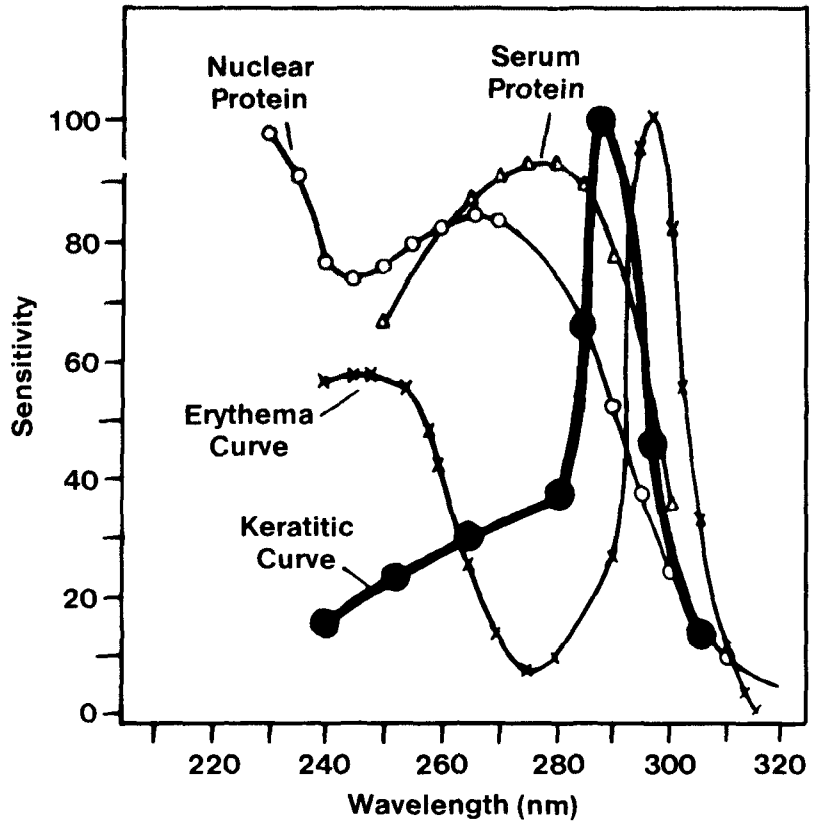

Figure 2. Action Spectra for Experimental Photokeratitis in the Rabbit Cornea and Erythema of the Skin. The absorption spectra for nuclear and serum proteins are also shown (from Cogan and Kinsey 1946).

One might think the action spectrum to be identical to the absorption spectrum for the chromophore which initiates the reaction; determination of the action spectrum has enabled us in some instances to identify the responsible chromophore for photobiologic reactions. However, the action spectrum for a response in vivo and the in vitro absorption spectrum of the chromophore may differ for many reasons, including that the absorption spectrum of the chromophore in vivo differs from that in vitro because of variations in pH, binding on other phenomena, or that the effective radiation received by the target chromophore in vivo is modified by the optical properties of the overlying tissue.

In addition to action spectra we can also describe biologic effectiveness spectra. These may be used to address possible changes in the magnitude of health effects of ultraviolet, such as those that might occur with solar radiation if the stratospheric ozone layer is altered. A biological effectiveness spectrum is the relationship between the photobiologic response and the wavelengths present in a specific source. It is obtained by multiplying the relevant points on the action spectrum curve (expressed as reciprocal dose) by the energy of the radiation of each wavelength present in the light source used. The integral of the area under the curve represents the biologically effective energy of that particular light source.

Action spectra are generally determined using monochromators to study the effects of narrow ultraviolet wavebands (approaching single wavelengths). However, interactions between different wavebands also may occur in producing biological effects. Interactions have been identified between UV-A and UV-B in the production of erythema and may occur between UV-A and UV-B in carcinogenesis. Such interactions are not normally addressed in the classical available action spectra but should be considered in determining likely responses to any particular source of ultraviolet radiation.

EFFECTS OF ULTRAVIOLET ON THE SKIN

We now summarize the effects of ultraviolet radiation on the skin, which are listed in Table 3.

Non-Neoplastic Effects

The role ultraviolet radiation plays in Vitamin D metabolism is a beneficial effect of ultraviolet radiation (Haussler and McCain 1977). Solar ultraviolet converts epidermal 7-dehydrocholesterol to previtamin D which undergoes a nonphotochemical, temperature-dependent, isomerization to Vitamin D3 which is transported from the epidermis by plasma Vitamin D binding protein. The bone disease rickets, which is caused by Vitamin D deficiency, was common in recent generations, particularly in those with heavily pigmented skin who lived in urban surroundings and were not exposed to sufficient solar radiation. However, now that Vitamin D is added to milk, this is no longer a significant problem in the United States.

Sunburn or solar erythema (Hawk and Parrish 1982) is associated with vasodilatation and inflammation of the skin. A variety of chemical mediators that appear to be responsible for erythema are released from the skin following ultraviolet exposure; the actual sequence of events seems to be quite complex. Among the changes is an alteration and depletion of Langerhans

cells, the major epidermal cell concerned with antigen presentation and the development of allergic and immune responses in the skin.

Ultraviolet radiation produces two types of tanning reactions (Quevedo, Fitzpatrick, and Jimbow 1985) in those genetically able to tan: immediate tanning due to darkening and redistribution of existing pigment; and the more important process of delayed tanning, one or more days after irradiation, in which there is production of new melanin pigment and proliferation of melanocytes.

Table 3. Effects of Ultraviolet Radiation on Human Skin

- Acute
  - Sunburn
  - Thickening of the Epidermis
  - Pigmentation
  - Vitamin D Production
- Chronic
  - Actinic Elastosis and Photoageing
- Carcinogenic
  - Nonmelanoma skin cancer
    - Actinic keratosis (precancerous)
    - Squamous cell cancer
  - Melanoma (?)
- Diseases Triggered by Ultraviolet, or Characterized by Photosensitivity
  - Genetic
    - Xeroderma Pigmentosum
    - Albinism, etc.
  - Nutritional
    - Kwashiorkor
    - Pellagra, etc.
  - Infectious
    - Herpes Simplex, Lymphogranuloma venereum, etc.
  - Immunologic
    - Lupus erythematosus
    - Pemphigus, etc.
  - Metabolic
    - Porphyria cutanea tarda, etc.

Immediately after sufficient exposure to UV-B reductions in DNA, RNA, and protein synthesis occur. Later, beginning within one day, increased synthesis of these substances with thickening and hyperplasia of the epidermis occurs. Both this thickening and the production of new melanin pigment give a measure of protection against further ultraviolet damage.

Ultraviolet radiation is the major cause of aging changes in the skin, particularly in those with fairer-skin colorations. These occur as a chronic effect and presumably reflect cumulative sun exposure and individual suscepti-

bility. These changes include patchy alterations in pigmentation, loss of the surface architecture, epidermal atrophy, telangiectasia (widening of small blood vessels), and the premalignant change of actinic keratoses. The elastic fibers of the dermis are damaged so that they become thick and coarse and lose their elasticity resulting in coarse, furrowed skin, a condition known as actinic elastosis. The action spectrum for actinic elastosis is undetermined but it is believed to include at least ultraviolet.

Apart from skin cancers, a number of skin diseases are either triggered by ultraviolet exposure or are manifested, at least in part, by excessive sensitivity to ultraviolet (photosensitivity) so that sun exposure makes their symptoms worse. Examples are listed in Table 3, including hereditary genetic diseases such as XP or albinism; nutritional deficiency states such as Kwashiorkor (protein-calorie deficiency) or pellagra (niacin deficiency); infectious diseases such as herpes simplex; immunologically mediated diseases such as lupus erythematosus; altered metabolic states including porphyrias; and others (Fitzpatrick et al. 1979). Although these diseases are common to various degrees, when skin cancers are included, sun-induced skin diseases account for more than half of all skin diseases seen by dermatologists among fair-skinned persons in areas with high sun exposure, such as rural Australia.

Nonmelanoma Skin Cancer

The skin neoplasms unequivocably associated with sun exposure include the premalignant actinic keratosis, basal cell carcinomas, and squamous cell carcinomas (Emmett 1973; Epstein 1983; Van der Leun 1984). The evidence that such tumors might be associated with solar radiation includes their increased prevalence on parts of the body habitually exposed to sunlight; in lightly pigmented and thereby less protected individuals; in areas of the world which have the greatest insolation; in individuals who spend more time outdoors; and especially in those who suffer from xeroderma pigmentosum. The highest incidences of such tumors are seen amongst those of Anglo-Saxon and Celtic descent in such areas as Queensland, Australia, and Arizona and New Mexico in the United States. Complete statistics are not available, but there is clearly a relationship between latitude and incidence of nonmelanoma skin cancers in Caucasians in the United States.

Although basal cell and squamous cell carcinomas are often grouped under the designation nonmelanoma skin cancer, they represent biologically distinct diseases that should be considered separately and indeed have different relationships to ultraviolet radiation. There are at least three reasons for this distinction. First, basal cell carcinoma and squamous cell carcinoma differ in their microscopic and histologic appearance as well as in their biologic behavior, pattern of growth, and tendency to metastasize. Second, comparisons between the sites of occurrence of squamous cell and basal cell carcinomas on the skin and the amounts of ultraviolet radiation these sites receive indicate that while squamous cell carcinomas almost all occur in heavily exposed skin, about one third of basal cell carcinomas in lightly pigmented individuals occur on customarily shaded sites of the face. The third indication of differences between basal cell and squamous cell carcinomas arises out of recent attempts to construct mathematical models relating the occurrence of various types of skin cancer to the amount of solar ultraviolet radiation received by the individual. This is a difficult area, partly because we do not have sufficient details about exposure to make good

models. However, the studies to date suggest that the basal and squamous cell tumors have different quantitative relationships to sun exposure (Scotto, Fears, and Fraumeni 1981). Data from various centers around the world also indicate that the ratio of squamous cell to basal cell carcinomas becomes higher as one approaches the equator.

Some individuals are much more prone than others to sun-induced skin cancers of all types. Phenotypic characteristics that are risk factors for skin cancer in controlled studies include fair complexion, light eye color, light original hair color, poor ability to tan, and easy and repeated sunburns. Persons of Celtic (Scottish, Irish, Welsh) descent may be particularly vulnerable, possibly even in the absence of these phenotypic characteristics. The risk is extreme in those with XP. Limited studies also suggest that subjects with actinic keratoses have less capacity to repair damaged DNA than controlled populations. In contrast to light-skinned people, skin cancer is relatively rare in deeply pigmented groups in whom basal cell epitheliomas are uncommon while squamous cell carcinomas generally occur on the lower extremities and do not appear related to ultraviolet radiation.

Much information concerning ultraviolet carcinogenesis and the factors that affect the process has been gained from studies in animals. It is easy to produce fibrosarcomas in many species from repeated ultraviolet irradiation. The hairless mouse has proven a particularly useful experimental model since, like humans, it develops squamous cell tumors. Basal cell tumors have been produced experimentally in rats using chemical carcinogens, but not to date in any species using ultraviolet.

Experimental factors shown to be important in causing squamous cell cancer include pigmentation, presence or absence of hair, stratum corneum thickness, wavelength of the irradiation, ambient temperature, wind, total ultraviolet dose, and the way the ultraviolet dose is fractionated. Experiments by Forbes, Davies, and Urbach (1978) suggest that delivery of the same amount of ultraviolet in divided doses, i.e., five exposures a week, was more effective at producing tumors than when delivered once a week. UV-B is the most efficient in producing cancers; UV-C is also effective. Although UV-A markedly accentuates acute skin damage from UV-B, conflicting results exist about whether UV-A augments UV-B carcinogenesis.

A number of different types of chemicals can augment the carcinogenic properties of UV-B. These include skin exposure to chemical carcinogens (such as polycyclic aromatic hydrocarbons, certain nitrosureas, and N mustard), promoting agents (such as croton oil, dodecane, and possibly all-trans retinoic acid), some but not all phototoxic agents (for example, 8 methoxypsoralen but not anthracene), skin irritants, and immunosuppressives. Certain agents have been shown to inhibit experimental ultraviolet carcinogenesis including caffeine, theophylline, certain antioxidants and some sunscreen agents. Some of these observations appear to relate directly to human experience. For example, an increase in squamous cell carcinomas has been observed in patients having immunosuppressive treatment following renal transplantation and in those who have been treated for psoriasis with 8-methoxypsoralen and UV-A (Stern, Zierler, and Parrish 1980).

Immunosuppression may play an important role in the development of ultraviolet-induced tumors. Kripke and her colleagues (Kripke 1981, 1982) have

shown that ultraviolet irradiation of mice results in specific susceptibility to transplantation with highly antigenic ultraviolet-induced cancers. This effect does not result from general loss of immune competence but rather from the production of supppressor T cells with antigen specificities directed toward ultraviolet-induced tumor antigens. The action spectrum for this effect is primarily in the UV-B.

Ultraviolet and Malignant Melanoma

Melanomas (Lee 1982) are malignant neoplasms that arise from melanocytes, the melanin producing cells found both within the skin and some other sites. Melanomas of the skin are much less common than basal cell and squamous cell carcinomas but are important because of their tendency to metastasize easily and kill the patient. In contrast to all other cancers except lung cancer, both the incidence and to a lesser extent death rates from melanoma appear to have been rising steadily over the last several decades in fair-skinned populations worldwide. This effect has been seen in England, Wales, the United States, Australia, New Zealand, Scandinavia, Israel, and elsewhere. A similar trend has been seen in Japan, but no clear trend exists in the mortality from melanoma of the skin among U.S. nonwhites. In the United States, the mean annual increase in death rates from malignant melanoma over the last 20 years has been about 3 percent for males and 2 percent for females. This increase is not due to changes in diagnostic proficiency; it has occurred despite an improvement in survival rates for those who develop melanomas. If age-specific death rates over a number of years are examined in terms of birth cohorts, we see that the trends are dominated by year of birth. This indicates steadily increasing risk. Interestingly, no such trends have yet been detected with regard to melanoma of the eye.

Although there is evidence that sunlight plays some role in melanoma genesis in white-skinned individuals, this relationship remains problematic and far from definitely proven. We lack an accepted animal model in which ultraviolet or sunlight reproducibly causes melanoma. Available epidemiologic studies are almost all ecologic and associate melanomas with some potential surrogate of sun exposure such as latitude of residence. Although it is often presumed that UV-B is the region of solar radiation responsible for causing melanoma (because it damages DNA), this supposition lacks proof, even if we accept a relationship to sun exposure.

Perhaps the single most convincing piece of evidence for a role for UV-B in the induction of melanoma is the high frequency of melanoma in XP. But even in this condition the repair defect is not confined to UV-B induced photoproducts, so that agents other than UV-B could conceivably account for this predisposition.

Melanomas occur in at least three distinguishable histologic forms which appear to have differing relationships to solar radiation. Lentigo maligna melanoma, which accounts for about 14 percent of melanomas, is slow growing and occurs characteristically on the heavily sun-damaged skin of the face of older, light-skinned, individuals. Nodular melanoma (32 percent) and superficial spreading melanoma (54 percent) occur mostly on the trunk and limbs and are less clearly related to sun exposure.

There are several observations that possibly link melanomas to sun exposure, but the evidence is not consistent. Melanoma is much more frequent in those who are light-skinned and those who sunburn easily. It is even more frequent in those who have certain types of pigmented moles called dysplastic nevi (Kraemer and Greene 1985). These moles tend to run in families and to a large extent, but perhaps not entirely, the familial tendency of melanomas is determined by the presence of these lesions. Melanomas are more frequent in those who sunburn easily and who have had severe or repeated sunburns in childhood; however, in contrast to most nonmelanoma skin cancers, melanomas are not usually on exposed parts of the body. Latitude studies have shown a broad relationship between melanoma in Caucasians and insolation, but studies are inconsistent. Migrant studies strongly support a childhood spent in a sunny location as an important factor in the later development of melanoma. Melanoma is a disease of higher socioeconomic classes and is not seen as much in those with the highest outdoor exposure. It has, therefore, been suggested that a causal factor for melanoma might be intermittent (i.e., weekend or vacation) high sun exposure, but this hypothesis awaits proof. Indeed the risk of melanomas in individuals seems to be less in those with increasing sun exposure, suggesting that individuals continually exposed to the sun have less risk either because of tanning or because susceptibles purposely avoid sun exposure, or both (Graham et al. 1985).

In any case, if solar radiation is a factor in causing human melanomas the relationship appears complex, and the distribution of the disease populations is probably not directly determined simply by total cumulative sun exposure.

ULTRAVIOLET EFFECTS ON THE EYE

The effects of ultraviolet radiation on the eye (Lerman 1980) are affected both by the amount of ambient radiation incident on the surface of the eye and by differential transmission through the ocular tissues. We have been studying the amount of radiation that may impact the corneal surface in outdoor workers. Only a small proportion of the ambient solar ultraviolet impinges on the eye; the amount varies with season, activity, reflecting surfaces in the vicinity, and whether or not the subject wears a hat or glasses. Plastic lenses are particularly effective in reducing the flux of UV-B at the surface of the eye. Although direct effects of ultraviolet on the retina are not generally expected in normal individuals because the radiation is absorbed in the lens, substantial ultraviolet reaches the retina in aphakic individuals.

The known effects of ultraviolet on eye are indicated in Table 4. The best known effect on the conjunctiva and cornea is acute photokeratitis, most effectively caused by radiation in the 288- to 290-nm wavelength region in which necrosis and death of corneal cells occur. The condition, known by such names as "welders flash burns" or "snow blindness," is characterized by a gritty sensation in the eyes, tearing, photophobia (sensitivity to light) and blepharospasm (spasm and closure of the eyelids). The eyelids are also often red. The symptoms occur after a latent period of from 30 minutes to 24 hours, which varies inversely with the dose. Symptoms are usually self-limited and heal within 48 hours. Permanent injury is rare.

Table 4. Effects of Ultraviolet Radiation on the Eye

Conjunctiva and Cornea
Photokeratoconjunctivitis
Chronic Actinic Keratopathy
Corneal Tumors
Benign Pterygia
Carcinoma of the Cornea (very rare)
Diseases Triggered by Ultraviolet
Herpes Simplex Keratitis
Recurrent Corneal Erosions, etc.
Lens
Nuclear Cataract
Retina
Retinal Damage (aphakics, others?)
Ocular Melanoma (?)

In chronic actinic keratopathy there are white or yellow-brown nodular opacities confined to the sites of the cornea covered by the lids. These have a restricted geographic location and are confined to areas of the world with high ultraviolet exposure in the eye (e.g., "Labrador keratopathy").

Ultraviolet radiation appears to be a major factor in developing pterygia and pingueculae, benign tumors of the conjunctivae and cornea, respectively. It can also trigger the development of certain corneal diseases including herpes simplex and recurrent corneal erosions.

The effect of ultraviolet on the human lens is of great interest. Cataracts can be experimentally produced in rabbits by ultraviolet radiation, which appears to exert an effect on the lens, at least in part, by acting on protein-bound tryptophan residues. Nuclear cataracts appear to be more frequent in human populations where increased ultraviolet exposure occurs, although studies that relate this exposure to individual ultraviolet exposure are very few (Pitts et al. 1986). With age there is an increase in pigments formed in the lens which may both contribute to nuclear cataracts and serve a photoprotective function in screening deeper tissues in the eye from radiation.

The retina is particularly sensitive to damage from shorter wavelengths of ultraviolet. There is no uniform agreement regarding the significance of this observation for normal people, but in aphakic individuals substantial opportunity for retinal damage seems to exist. Two recent studies have raised the possibility that ocular melanoma, a relatively rare but serious neoplasm, might be related to sun exposure (Tucker et al. 1985). If this finding is correct, it remains speculative whether the ultraviolet portion of solar radiation is responsible.

ROLE OF PHOTOSENSITIZING SUBSTANCES

A number of foreign substances act as photosensitizers in that they absorb ultraviolet (or visible) radiation and augment or change the tissue response to this radiation (Emmett 1979). Well-known photosensitizers include several components of coal tars and pitches; chemicals produced by plants including psoralens; a variety of dyes, drugs, and antibacterials in common use; and photoinitiators used for industrial photochemical processes. Potential photosensitizers are increasingly common components of products used in modern life.

The most common reactions are designated as "phototoxic" and occur as direct toxic effect from the chemical and ultraviolet radiation without mediation of the immunologic system. A variety of reactions are produced on the skin, including severe reactions resembling sunburn and severe blistering. In the eyes, photokeratoconjunctivitis and cataracts may result. As mentioned previously, some photosensitizers, notably 8-methoxypsoralen in combination with UV-A, have been shown to be carcinogenic both in experimental animals and humans.

More rarely, individuals can develop photoallergy, an allergy of the skin dependent on exposure to both the chemical and ultraviolet radiation. Photoallergic reactions are not known to result in cancer but a so-called persistent light reaction can ensue which will persist for years with trivial amounts of sun exposure, even in the absence of further contact with the inciting chemical.

CONCLUSION

We have reviewed the various effects of ultraviolet on human health. In considering the health effects of ozone modification, we are particularly concerned with the chronic effects of ultraviolet radiation. These are not determined solely by the amount of ultraviolet radiation but also by other factors. The three major factors involved are exposure to ambient solar radiation, individual susceptibility, and personal behavior. From the point of view of human health we cannot sensibly address the issues involved without considering all three factors.

Future studies of chronic effects will advance the field to the extent that they gather information on individual susceptibility and behavior, and in the case of studies of tumors, by relating to or distinguishing individual tumor types. Future risk assessments will only make medical or biologic sense to the extent that they take these factors into account.

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Ozone Depletion and Ocular Risks From Ultraviolet Radiation

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INTRODUCTION

Because depletion of the ozone layer (Watson et al. 1986) increases ultraviolet (UV) radiation, and since ambient outdoor levels of UV radiation have been implicated as a risk factor for retinal damage and cataract formation (Waxler, In press), expected atmospheric changes may increase the risk of eye damage.

Ultraviolet (UV) radiation can damage the cornea (Pitts 1973), the crystalline lens (Pitts et al. In press), the ocular photoreceptors (Massof et al. In press), and the retinal pigment epithelium (Ham et al. In press). This damage may contribute to long-term problems such as retinal degeneration (Newsome et al. In press), visual aging (Owsley et al. In press), impaired visual development (Fulton et al. In press), and cataracts (Pitts et al. In press). These analyses were made to determine whether optical radiation has the potential to produce long-term visual health problems and, if so, under what conditions they might occur. A risk assessment was conducted (Waxler, In press) to focus attention on estimating the risks that optical radiation poses for long-term visual health problems, the conditions under which they might occur, and the ways by which we can minimize the occurrence of such problems on the basis of what we know. This risk assessment will provide the basis for judging the extent to which depletion of the ozone layer increases these problems.

VISUAL HEALTH PROBLEMS

To provide some informed guesses about the likelihood that long-term visual health problems could result from exposure to optical radiation, we need to specify the visual health problems about which we are concerned, and then to analyze the evidence of involvement of optical radiation in these problems. First, the potential health problems already have been identified. They are cataracts, stable retinal disorders, retinal degeneration,

visual aging, and developmental disorders. Second, because these long-term problems stem from similar photobiological and visual science principles, the following series of questions were devised to help in this risk assessment:

- Does the ocular tissue involved in the disorder absorb optical radiation?
- Does the absorbed radiation induce bioeffects in this tissue?
- Are these radiation bioeffects a hazard to this tissue?
- Can the disorder be deduced from the damage induced in the ocular tissue by the radiation?
- Is there evidence confirming that the disorder is caused, wholly or in part, by optical radiation?
- Can the probability that optical radiation induces this disorder be estimated?

Cataracts

First, we know that the crystalline lens absorbs ultraviolet radiation (Boettner and Wolter 1962; Kinsey 1948; Cooper and Robson 1969). Moreover, UV radiation can induce biochemical and histological effects in the crystalline lens of various animals (Pitts et al. 1977; Zigler and Goosey 1981). In addition, some of these bioeffects are related to UV-induced opacities in human and animal lenses *in vitro* (Lerman 1983; Varma et al. 1983). Although there are a number of limitations to extrapolating these data to the *in situ* lens of the human eye (Pitts et al. In press), the deleterious bioeffects do provide a basis for identifying cataracts as a hazard of ultraviolet radiation. Various studies have determined the wavelengths and radiant exposures needed to induce cataracts (Pitts 1973; Pitts and Cullen 1981; Schmidt and Zuclich 1980; Zuclich and Connolly 1976). Several photochemical pathways have been described whereby cataracts could be induced in humans (Jose 1978; Zigman 1981). Moreover, there are similarities between UV-induced cataracts and human cataracts of unknown etiology that provide an added basis for postulating a risk of UV cataracts in humans (Lerman and Borkman 1976). Finally, there are clinical reports of photosensitized cataracts in humans (Lerman et al. 1983) and, more importantly, epidemiological evidence that demonstrates an association between exposure to ultraviolet radiation and cataracts (Hollows and Moran 1981; Hiller, Giacometti, and Yuan 1977; Taylor 1980; Hiller, Sperduto, and Ederer, 1983; Ederer, In press). Thus, there is sufficient data to identify cataracts as a risk of ultraviolet radiation. However, the uncertainties associated with this evidence limit the utility of this epidemiological data for estimating the risk of human cataracts from UV radiation.

Stable Retinal Disorders

Studies have been conducted that provide a chain of evidence on which to postulate that optical radiation can contribute to human retinal disorders that are not progressive, i.e., stable retinal problems. This chain starts with the knowledge that UV-B, UV-A, and light are absorbed by various retinal

tissues (Wolbarsht 1976; McGuinness and Proctor 1973). Moreover, the amount of radiant energy incident on the retina depends on the transparency of the cornea and lens, and on pupil diameter. Next, a large number of bioeffects of these wavelengths have been identified as being hazardous to the retina (Massof et al. In press; Ham 1984). Further, empirical estimates have been made of the domain of time, intensity, and wavelength that can induce damage to the pigment epithelium, the photoreceptors, and the inner retina. These estimates provide sufficient quantitative evidence to establish safety standards to protect people from the short-term retinal damage which could be induced by lasers and other intense sources of optical radiation (Ham 1984; Sliney and Wolbarsht 1980). There is, moreover, sufficient evidence of additive and persistent changes in the monkey and human retina to hypothesize that some stable long-term visual impairments in humans may be related to optical radiation. There are reports that optical radiation produces retinal damage hours, days, months, and years after irradiation. Although it is sparse, this evidence is instructive. For example, sungazing by humans has been reported to produce persistent, evolving, and delayed alterations in the visual system. Craik reported that aniseikonia may persist for years (Cavonius, Elgin, and Robbins 1974). Pigmentary patches and blind spots have been reported to evolve in a complicated fashion over many months after solar retinopathy (Loewenstein and Steel 1941). In addition, late complications resulting in reduced visual acuity have been described (McFaul 1969). Furthermore, there are several reports in humans of prolonged and even cumulative impairments in dark adaptation following extended viewing by humans of skylight (Hecht et al. 1948; Clark, Johnson, and Dreher 1946) or bright blue, violet (Brindley 1953), and ultraviolet (Wolf 1949) radiation. Also, there is at least one report of persistent visual impairment resulting from accidental exposure to ultraviolet radiation from a welding arc (Naidoff and Sliney 1974). Even more important is the description by Tso and Woodford (1983) of sub-RPE neovascularization and late impairment in fluid transport after several years of evolving changes in retinal pathology following excessive exposure to optical radiation. Although long-term observations of the monkey retina damaged by UV have not been conducted, some of the fluorescein leakage that has occurred within days or weeks following irradiation suggest longer term sequelae.

Some of these effects are the result of injury to the retina, which was ophthalmoscopically visible; others resulted from exposures to optical radiation that did not produce ophthalmoscopically visible damage. Most important are two demonstrations that the addition of subthreshold exposures separated by several days induces retinal damage (Griess and Blankenstein 1981; Kuwabara and Okisake 1976). The data strongly suggest that retinal damage induced by optical radiation can accumulate over days. This is especially important since the concern about long-term visual health problems necessarily involves consideration of the intermittent nature of exposure to emissions from multiple sources over an extended period of time. Split-dose experiments using UV-A radiation of the monkey retina are in progress and strongly suggest that the damage accumulates over days to produce pathological changes that persist for months. Photobiological principles suggest that a similar cumulative effect would occur in the UV-B region.

Retinal Degeneration. There are some reasons to suspect that retinal damage induced by ultraviolet radiation can be unstable, that is, it can produce progressive damage. The retina of monkeys can be damaged by ultraviolet

radiation (Ham 1984; Peyman, Sloan, and Lim 1983). This damage to the retinal pigment epithelium, to the photoreceptors, and to the neurons is dose-dependent, photochemically mediated, and cumulative over hours and days. Although very few long-term observations have been made on the primate retina following excessive exposure to optical radiation, there are theoretical reasons to suspect that a retina compromised by disease or age would be more vulnerable to any degenerative changes that could be induced by optical radiation (Young 1981). The combination of short-wavelength optical radiation, oxygen, chromophores, and photosensitizers in the retina is potent with possibilities for producing retinal degeneration, although direct evidence of the exacerbation of retinal degeneration by optical radiation has been obtained only in rodents (LaVail and Battelle 1975). In addition, the higher retinal doses of UV received by aphakes and pseudophakes make these individuals especially vulnerable to cystoid macular edema (Kraff et al. 1985). Fluorescein leakage occurs following exposure of the retina of the aphakic monkey eye to UV-A radiation (Peyman, Sloan, and Lim 1983; Tso et al. Work in progress), but comparable studies using UV-B radiation have not been conducted. Therefore, retinal degeneration should be considered a risk of excessive exposure to ultraviolet radiation.

Very little research has been conducted on primates, on diurnal animal models of human retinal degenerations, or on retinas compromised by chemicals, age, or other agents. The striking evidence of long-delayed and persistent changes in the monkey retina following optical radiation, coupled with some clinical evidence in humans, suggests that research on primates needs to be a priority.

Aging Disorders. Deterioration of the visual system as individuals age is a fact (Owsley et al. In press). The likelihood that optical radiation contributes to this deterioration is high for several reasons. First, the cellular pathology observed in older individuals is similar in appearance to radiation-induced damage (Kuwabara 1979). Second, the ophthalmoscopic appearance of the aged retina is sometimes similar to a retina exposed to optical radiation (Guyer et al. 1986). Third, some of the kinds of vision loss described in the aged are consistent with the losses that could be produced by optical radiation damage (Klein 1958; Jaffe, de Monestario, and Podgor 1982). Fourth, the accumulation of lipofuschin material in the RPE and other changes in the retina suggest that the aged retina has less capability of repair (Feeney-Burns, Berman, and Rothman 1980). The retina of the human aphakic eye has three times more macular drusen and pigmentary changes than the retina of the phakic eye, suggesting that UV plays a role in aging the human retina (Guyer et al. 1986).

Optical radiation may have quite different visual health consequences for eyes with and without ocular disease. Optical radiation may accelerate the deterioration of central vision in older individuals with central retinal disease, whereas, in those free of ocular disease, optical radiation may impair paramacular and peripheral vision more than foveal vision. This interpretation is offered to reconcile the facts of visual loss outside the macula in disease-free aged eyes (Owsley et al. In press) with Young's prediction that the central retina will exhibit the major effects of lifetime retinal exposure to optical radiation (Young 1981). This ad hoc explanation is not very satisfactory but it does indicate the need to temporize theory with data. Other interpretations also are possible, e.g., those individuals with

central retinal disease may have had a different exposure history or some genetic vulnerability.

Given these facts and theoretical considerations, exposure of the aged retina to more ultraviolet radiation than permitted by the phakic eye probably is hazardous. The retina of the aged individual is exposed to more radiation than phakics receive when the crystalline lens is extracted without placing a comparable filter in front of the retina, even when ordinary sunglasses are used.

Research is needed to determine the extent to which optical radiation is a factor in the deterioration of the vision of the elderly. In the meantime, we should take practical steps to protect our eyes from excessive optical radiation, and thus prolong our visual lifetime.

Development Disorders. While there are several reasons to suspect hazardous effects of optical radiation on visual development, almost no research has been conducted on the developing primate retina. In fact, there is very little experimental data on the exposure of the developing retina of any species.

Glass et al. (1976) have reported that the probability of retinopathy of prematurity (ROP) is highest in infants exposed to more light during their hospital stay. This evidence is consistent with the evidence for the interaction of oxygen and light in retinal damage (Lerman 1980). The action spectrum for this effect is unknown but UV-B and UV-A probably play a role. Furthermore, there is a large variety of sources of optical radiation and situations in which infants are exposed to optical radiation. Some of the same evidence that gave rise to suspicions about the role of optical radiation in retinal degeneration and visual aging is relevant to the potential hazards to visual development, i.e., short-wavelength radiant energy incident on the retina, short-wavelength chromophores in the retina, dose-dependence of retinal damage, cumulative effects, long-duration effects, and delayed effects. In addition, special properties of the developing visual system might decrease injury threshold, such as more transparent ocular media and different densities of chromophores and screening pigments, or might increase the vulnerability of infants, such as long periods of post-natal retinal development (especially foveal) and early dependence on nonfoveal visual fields. Thus, the long periods required for many visual processes to mature suggest a window-of-vulnerability during which time optical radiation might alter later visual performance, especially if optical radiation alters the spatial and temporal summation properties of the neural retina.

Even though there is little experimental data on the effects of optical radiation on the developing retina, photobiological and visual science evidence is sufficient to postulate that exposure to optical radiation may cause disorders of visual development.

CONDITIONS AFFECTING RISKS

Exposure Variables

Several exposure conditions affect the likelihood of long-term visual impairment. The fundamental parameters are wavelength, level of radiant exposure, and duration of radiant exposure. Ocular damage occurs at lower radiant exposures and shorter exposure durations for shorter wavelengths. More intense repetitive exposures at various wavelengths can cause eye damage, as can exposures of longer duration at intermediate levels of radiation. Depletion of the ozone layer increases the ambient level of UV-B radiation and therefore also increases the risk of eye damage.

Biological Variables

A number of biological factors influence the potential for visual impairment from exposure to optical radiation. Pupil size and the absorption characteristics of ocular tissues are quite important. Lens transparency and yellowing, aphakia, and pseudophakia are important factors in estimating how much retinal damage will occur. Lens yellowing may promote additional opacification of the lens by increasing the absorption of UV and blue light; on the other hand, the retinal damage threshold will be increased. An increase in oxygenation and temperature in ocular tissues will greatly increase the potential for visual impairment. Also, the developing infant eye and the aging eye may be especially vulnerable to the damaging effects of radiation. The retina may be more vulnerable to radiation effects when it is degenerating because of genetic or other toxic effects. The cumulative effect of photochemical events and tissue repair rates are crucial biological variables influencing the likelihood of long-term visual health problems.

Long-Term Risk--An Exercise in Its Estimation

This section attempts to estimate the domain of optical radiation risk to long-term visual health. This domain refers to a subset of the wavelength and radiant exposure parameters. This is an effort to establish a boundary between those exposure conditions that are likely to produce visual health problems and those that are not.

Determine Radiant Exposure Associated With Disorders. First, to establish such a boundary, the radiant exposures of each particular ocular disorder must be determined.

The Possible Effect of UV Exposure on Cataracts. Some of the epidemiologic data on sunlight and cataracts can be used to estimate the radiant exposure at UV-B wavelengths (Hollows and Moran 1981; Hiller, Giacomett, and Yuan 1977; Taylor 1980). Each of these studies found that cataracts were positively associated with sunlight exposure when the latter exceeded an annual level of 2500 Minimal Erythemal Doses (MEDs). Luckiesh et al. (1930) reported the MED in the UV-B to be about 0.004 joules per square centimeter. Therefore, 2500 MED equals 10 joules per square centimeter annually. The daily radiant exposure would be the annual dose divided by 365 days, 0.027 joules per square centimeter and a three-hour daily exposure would be 0.0068 joules per square centimeter. On the other hand, if we use 348 joules per square centimeter as the value (Parrish, Jaenicke, and Anderson 1982) for the MED at 300 nm, the

three-hour estimated dose becomes 0.06 joules per square centimeter. Another estimate can be derived by using the local ambient level at 310 nm at 15°N reported by Johnson et al. (1976) and the epidemiologic data reported by Zigman et al. (1979). This estimate is 0.9 joules per square centimeter.

Several estimates of the UV-A radiant exposure needed to induce cataracts can be derived or have been reported. If only the UV-A wavelengths emitted by the sun are responsible for the cataracts associated with 2500 MEDs insolation, then the annual radiant exposure associated with cataracts would be 140,000 joules per square centimeter, approximately 395 joules per square centimeter daily and 98.8 joules per square centimeter for a three-hour daily exposure; this assumes (Johnson, Mo, and Green 1976) that one MED at 365 nm equals 57.7 joules per square centimeter. Another estimate can be obtained from Lerman (1980). He estimated that accidental exposure of the the human eye to a UV-A photopolymerization device produced cataracts at 21.6 joules per square centimeter. Finally, the Zigman et al. (1979) epidemiologic data suggest an estimate of 0.44 joules per square centimeter, using the local ambient level (Pitts, Bergmanson, and Chu 1983) at 340 nm at 15°N.

Experimental levels of radiant exposure needed for UV cataractogenesis are summarized by Pitts et al. (In press). Several values were selected for comparison to the above epidemiologic estimates. These estimates are summarized in Table 1. The lowest radiant exposure for UV cataractogenesis is at 300 nm as estimated from the epidemiologic data. Moreover, even when the joule equivalent for the MED used is 348 joules per square centimeter rather than 4.0 joules per square centimeter, the three-hour radiant exposure estimate of the former is only one log unit higher than the latter. The Zigman et al. (1979) estimate is only 0.3 log units higher than this high estimate. Experimental estimates are in this intensity range. These comparisons strongly suggest that decades of exposure to UV-B induces cataracts in humans at doses comparable to that suggested by the experimental evidence. On the other hand, comparison of these UV-B estimates with the UV-A epidemiologic estimates clearly demonstrates that higher doses of UV-A than UV-B are needed to induce cataracts. However, how much higher is not clear. The estimates based on the Hollows and Moran (1981); Hiller, Giacometti, and Yuan (1977); and Taylor (1980) data correspond closely to the experimental data, suggesting that 4.0 log units more radiant exposure are needed at UV-A than at UV-B wavelengths. On the other hand, the UV-A estimate based on either the Zigman or the Lerman data suggest that only 1.5 log units higher doses are needed.

The Possible Effect of UV Exposure on Retinal Problems. The following estimates of the level of radiant exposure needed to induce long-term retinal problems assume a three-hour daily exposure additivity over days and additivity over wavelength. When the data used for the estimation were based on an exposure of less than three hours, the level of radiant exposure was calculated based on the particular duration used in that study (i.e., 1000 seconds). Evidence that the damaging effect would accumulate over a period of time at least as long as three hours provides a critical bridge between these shorter durations of exposure (higher dose rate). On the other hand, when the data were based on exposures longer than three hours, dose was prorated to a three-hour duration. For broad-band sources of optical radiation, wavelength additivity was assumed and the estimate was based on the total integrated dose reported.

Table 1a. Radiant Exposure for Cataractogenesis: Experimental

Wavelength Band	Radiant Exposure (Jcm^{-2})	Exposure Duration (s)	Corneal Irradiance (Wcm^{-2})
UV-B	1.2×10^{-1} r[3]	191.5r	6.27×10^{-4} r
	4.5 r[3]	6374r	7.06×10^{-4} r
	1.26×10^{1} r[3]	4749r	2.65×10^{-3} r
UV-A	5.06×10^{1} r[3]	3.6×10^{4} r	1.405×10^{-3} r
	1.0×10^{2} r[3]		

Table 1b. Radiant Exposure for Cataractogenesis: Epidemiologic

Wavelength Band	Radiant Exposure (Jcm^{-2})	Exposure Duration (s)	Corneal Irradiance (Jcm^{-2})
	6.8×10^{-3} d	1.08×10^{4} a	2500MED[1] r[23,24,25]
UV-B	6.0×10^{-2} d	1.08×10^{4} a	2500MED[2] r[23,24,25]
	9.0×10^{-2} d	1.08×10^{4} a	1.3×10^{2} r,a[70,71]
	3.24×10^{-1} d	1.08×10^{4} a	$3.0 \times 10^{-5} Wcm^{-2}$ r*
UV-A	4.5×10^{-1} d	1.08×10^{4} a	6.56×10^{2} r[70,71]
	9.88×10^{-1} d	1.08×10^{4} a	2500MED[3] r[23,24,25]

r - reported
d - derived
a - assumed
1 - 1.0 MED = $4.0 \times 10^{-3} Jcm^{-2}$ r,a[68]
2 - 1.0 MED = $3.48 \times 10^{2} Jcm^{-2}$ r,a[69]
3 - 1.0 MED = $5.77 \times 10^{1} Jcm^{-2}$ r,a[69]
* - Dose rate reported to be associated with cataracts induced by dental photopolymerizer (Cole et al. 1985)

The only human data from which one could derive an estimate of the radiant exposure of UV that could damage the retina were in Hecht et al. (1948) and Clark et al. (1946). These data showed that staring at skylight for several hours induced an abnormal retardation of dark adaptation. Since rhodopsin has an absorption ban in the UV-A (Kurzel, Wolbarsht, and Yamanashi 1977), this deficit could have been due to the ambient outdoor UV-A. If the ambient level of UV-A at the cornea was about 0.09 joules per square centimeter as suggested by Ham and Mueller (1982), then the retinal radiant exposure might have been about 0.009 joules per square centimeter in the Hecht and Clark studies. Experimental estimates of UV retinal damage in monkeys have been few. Schmidt and Zuclich (1980) found the threshold at 325 nm to be 10 joules per square centimeter. Recent evidence in phakic rabbits (Pitts, Bergmanson, and Chu 1983) and rats (Rapp, Jose, and Pitts 1985) suggests that the radiant exposure necessary to damage the retina is even lower at 300 nm. The current threshold for 300 nm damage to the monkey retina is approximately 0.6 joules per square centimeter. Ham and Mueller (1982) found that the aphakic monkey has thresholds of 5.0 joules per square centimeter at 325 nm, 5.4 joules per square centimeter at 350 nm, and 8.1 joules per square centimeter at 380 nm. These estimates are summarized in Table 2. Estimates are provided for wavelengths longer than 400 nm to compare the effectiveness of various spectral regions.

Griess and Blankenstein (1981) have shown that the damage at 441 nm is cumulative over days, thus, not only verifying the radiant exposure needed to produce the damage, but also demonstrating that one-half the energy can be delivered 24 hours later and still damage the retina! Preliminary data (Tso et al. Work in progress) show that a similar effect occurs with UV-A radiation. UV-B probably produces a comparable effect, although this is an extrapolation based on photobiological principles, not on direct split-dose evidence.

Identify Ambient Levels and Compare to Radiant Exposure Estimates. Ambient levels of optical radiation have been measured at many geographical locations around the world. Johnson, Mo, and Green (1976) have measured solar radiation as a function of latitude from 305 to 340 nm. These data are adjusted for three-hour daily exposures. Since their data included only wavelengths up to 340 nm, the solar spectral radiance reported by Sliney and Wolbarsht (1982) was used for wavelengths longer than 340 nm. Their spectrum for the "summer sun near zenith" was multiplied by a solar disc size of 0.00006 sr to obtain the solar spectral irradiance and then multiplied again by the number of seconds in a three-hour exposure to obtain the solar radiant exposure. Several other sources are available for more detailed analytical research on ambient levels of solar radiation (Green, Sawada, and Shettle 1974; Green, Cross, and Smith 1980).

The relationship of these outdoor ambient levels to the radiant exposure estimates for cataracts and retinal disorders should be noted. Cataracts can result from outdoor ambient levels of UV-B and UV-A; however, UV-B is much more effective. Ozone depletion would increase ambient levels of UV-B radiation much more than UV-A radiation. Within the UV-A region there is considerable variability in the estimates. The possible bases for these differences will be discussed later. Ambient UV-A levels outdoors seem to be sufficiently intense to damage the retina. Most damage thresholds between 400 and 760 nm are one or two log units above ambient light levels outdoors with

Table 2. Radiant Exposure for Retinal Damage

Wavelength (nm)	Radiant Exposure (Jcm^{-2})	Exposure Duration (s)	Retinal Irradiance (Wcm^{-2})
	1.0×10^{1}d	8.0×10^{-1}r	1.3×10^{1}d[17,77]
	5.0r		1.0×10^{2}r.....5.0×10^{-2}r[77]
	5.1r		1.0×10^{3}r.....5.1×10^{-3}r[77]
	5.4r		1.0×10^{2}r.....5.4×10^{-2}r[77]
	5.5r		1.0×10^{3}r.....5.5×10^{-3}r[77]
	8.1r		1.0×10^{2}r.....8.1×10^{-2}r[77]
	9.3r		1.0×10^{3}r.....9.3×10^{-3}r[77]
	9.0×10^{-2}d	1.08×10^{4}a	8.5×10^{-6}d[39,40,77]
	9.0×10^{-3}d	1.08×10^{4}a	8.5×10^{-7}d*
	1.5×10^{1}r	1.0×10^{2}r	1.5×10^{-2}r[77]
	2.3×10^{1}r	1.0×10^{3}r	2.3×10^{-2}r[77]
	3.0×10^{1}r	1.0×10^{3}r	3.0×10^{-2}r[80]
	5.0×10^{1}r	1.0×10^{3}r	5.0×10^{-2}r[80]
	2.2×10^{1}r	1.08×10^{4}a	2.0×10^{-3}r[44,7]
	2.57×10^{1}r	1.0×10^{2}r	2.57×10^{-1}r[47,**]
	1.3×10^{1}r	1.0×10^{2}r	1.3×10^{-1}r[47,**]
	6.4r		1.0×10^{2}r.....6.4×10^{-2}r[47,**]
	8.52×10^{-1}d,r	4.8×10^{3}r	2.0×10^{-4}d[58,##]
	9.0×10^{1}r	1.0×10^{3}r	9.0×10^{-2}r[80]
	1.2×10^{2}d	3.2×10^{1}r	3.75d[81,82]
	3.0×10^{1}r	6.0×10^{2}r	5.0×10^{-2}r[83]
	3.0×10^{1}r	9.0×10^{2}r	3.3×10^{-2}r[83]
	3.0×10^{1}r	1.02×10^{3}r	2.9×10^{-2}r[83]
	3.0×10^{1}r	1.2×10^{3}r	2.5×10^{-2}r[83]
	1.1×10^{2}r	1.0×10^{3}r	1.1×10^{-1}r[80]
	1.08×10^{2}r	1.08×10^{4}r	1.0×10^{-2}r[44]
	1.0×10^{-1}r	1.0×10^{4}r	1.0×10^{-5}r[85]
	6.0×10^{-3}r	1.0×10^{4}r	6.0×10^{-7}r[85]
	3.0d		1.08×10^{4}a.2.8×10^{-4}r[49,121]
	5.0d		1.08×10^{4}a.4.6×10^{-4}r[49,121]
	1.3d		1.08×10^{4}a.....1.2×10^{-4}r[84]
	1.0×10^{-2}r	1.08×10^{4}a	9.3×10^{-7}d[34,39,40]
	7.5×10^{2}r	1.0×10^{3}r	7.5×10^{-1}r[80]
	1.08×10^{2}r	1.08×10^{4}r	1.0×10^{-2}r[44]
	9.0×10^{2}r	1.0×10^{3}r	9.0×10^{-1}r[80]
	9.5×10^{2}r	1.0×10^{3}r	9.5×10^{-1}r[80]

r - reported
d - derived
a - assumed
* - assumes 10% corneal exposure
# - R.G. Allen, personal communication
** - additivity over days at 1.0, 0.5 and 0.25 times threshold dose
- R.G. Allen, personal communication

the sun at zenith. However, several estimates are within 0.5 log units of outdoor ambient levels.

Determine Proportion of Ambient Likely to Be Incident on the Cornea. So far we have assumed that all of the ambient radiation in a three-hour period was incident on the cornea. However, Cole et al. (1985) have demonstrated that only 25 percent of ambient radiation reaches the skin of the face of a human standing upright and looking forward. Furthermore, in a standing position, the corneal dose may be only 10 percent of ambient due to shielding from the brow ridge and the corneal grazing angle in the ultraviolet (Wolbarsht 1982). However, an individual prone on his back with eyes open could receive a 100 percent corneal dose of ambient. On the other hand, Sliney (1986) and Rosenthal (1985) report higher ocular irradiances of UV-B from reflective surfaces on the earth's surface than from skylight.

These considerations suggest that cataracts associated with UV ambient levels may be due to corneal doses 1.0 log unit lower than the ambient level. Since the Hecht et al. (1945) and Clark, Johnson, and Dreher (1946) data are based on staring at the sky, 100 percent of ambient level is an appropriate value for their data. However, for those individuals who do not stare at the sky, the corneal dose may be 1.0 log unit lower than the ambient radiation.

Determine Proportion of Ambient Level to Which an Individual Is Likely to Be Exposed and Number of Days Exposed Per Annum. The variety of physical, cultural, and occupational environments in which people live is enormous. The previous discussions assumed that everyone is exposed to ambient outdoor levels 365 days per annum, three hours per day. Situations exist where people may be exposed to much more or much less than this amount.

Setting Risk Boundaries. Most of the estimates of radiant exposure that can damage the eyes are within 1.0 log unit of outdoor ambient levels. Therefore, one risk boundary can be established as 1.0 unit below the average outdoor ambient levels to establish a safety factor. This boundary should be moved lower to take into account increases in UV-B radiation that are caused by ozone depletion. The implication is that radiant exposure of the eye for three hours at levels above this boundary (the pink area) is probably a long-term visual health risk, i.e., the "probable risk" area.

Since there are some estimates that fall below this region of probable risk, a lower boundary was constructed to take these estimates into account, as well as certain worst-case conditions. For example, the epidemiologic estimates for cataracts were derived as if the effects occurred independently at only two wavelengths, 300 and 365 nm, an unlikely possibility; cataractogenesis due to broad-band UV exposure is probably additive across wavelengths. (Note: As a matter of fact, there isn't even any experimental evidence that UV at 365 nm can induce cataracts in vivo at doses below 100 joules per square centimeter.) As a consequence, the lower boundary could be set two log units below the upper boundary. In addition, these epidemiologic studies are not very precise, so that perhaps cataracts are associated with a lower number of annual MEDs.

If certain worst-case assumptions are made, such as subthreshold effects, genetic susceptibility, exogenous photosensitivity, poor nutrition, and

frequent exposure to ultraviolet radiation, then perhaps the lowest radiant energy at which cataracts might be induced is an order of magnitude lower than the lower boundary. However, the empirical estimates already may represent worst-case conditions; for example, cumulative effects over time and wavelength were assumed in establishing the estimates. If worst-case assumptions are accepted, then perhaps the reported estimates should be lowered by an order of magnitude at wavelengths shorter than 460 nm. Some of the worst-case assumptions are aphakia and pseudophakia without blue and ultraviolet blocking filters, transmittance of infant lenses close to 1.0, genetic and disease susceptibilities, exogenous photosensitization, and additivity of damage over days. Each of these is a special case requiring clinical management.

Although some of these estimates are based on sparse data and assume worst-case conditions, they provide some prediction of the wavelength-radiant exposure domain within which optical radiation can be expected to produce long-term visual health problems in the primate eye. Therefore, to conduct critical tests of long-term visual health problems, wavelengths in the blue and ultraviolet regions should be used at radiant exposures from as low as approximately 0.1 joules per square centimeter to 0.000001 joules per square centimeter, respectively.

Reduce Invisible Radiation of the Eye. People in outdoor occupations should protect their eyes. Reducing the amount of ocular irradiation by using hats, umbrellas, or sunglasses is a simple precaution that can be taken to avoid potential long-term visual impairment. Shielding the eyes from sunlight is especially valuable on bright sunny days on a sandy beach or snow field. Sunglasses that absorb the proper wavelengths certainly should be worn when staring into skylight. One should never gaze directly at the sun or an eclipse, even when wearing sunglasses.

While sunglasses have been available for many years, questions have been raised about their effectiveness in protecting the eyes from ultraviolet radiation (Sterne 1984). Although voluntary standards (ANSI Z 80.3) exist for nonprescription sunglasses (American National Standards Institute 1977), there are no standards for prescription sunglasses. Therefore, there is no assurance that there is sufficient filtration of ultraviolet radiation in prescription sunglasses. While the Sunglass Association of America claims that those nonprescription sunglasses made in compliance with the voluntary standard provide adequate protection from UV radiation (Loomis, personal communication), the consumer has no way of knowing whether any particular brand conforms to this standard. Furthermore, there is disagreement about whether this standard is sufficiently stringent, especially in the UV-A region. In addition, there may be sunglasses on the market that are so dense in the visible region that the pupil can be dilated sufficiently so that the partial UV filtration is negated by the increased pupil diameter. Various proposals have been made to solve these problems and they are under vigorous discussion within the ANSI Z-80 Committee and within the Food and Drug Administration. Some of these proposals are as follows:

- Require each pair of sunglasses to have a tag with the spectral transmittance on it.

- Require a "sunscreen" eye protection rating with each pair of sunglasses.
- Require certification that the sunglasses are made in conformance with the voluntary standard.
- Increase the voluntary density requirement in the UV.
- Require that prescription sunglasses conform to a standard comparable to the voluntary nonprescription standard.

Some manufacturers urge consumers to purchase expensive sunglasses which may not provide much more protection than much less expensive sunglasses. Clearly some kind of sunglass standard is needed to ensure that both prescription and nonprescription sunglasses reduce the corneal level of radiant exposure below the levels associated with cataracts and retinal damage.

UNCERTAINTY

Until there is a more precise understanding about the role of optical radiation in visual development, visual aging, retinal degeneration, photosensitized reaction, and cataracts, there will be uncertainty about whether particular protective measures provide too much or too little protection. People are exposed to optical radiation from a large number of sources over varying periods of time for an entire lifetime. In addition, depletion of ozone over time and in certain geographical regions lends more uncertainty. No matter where the maximum permissible exposure limit is established for immediate ocular damage, ambient outdoor levels of UV may approach this limit under some conditions. Until these limits are related to specific long-term visual health problems, protective measures should be based on some worst-case estimates. This may mean that "overprotection" will be established, but people will be better served by using too much protection than by using borderline or insufficient protection.

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Overview of Our Current State of Knowledge of UV Effects on Plants

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Fifteen years ago, we virtually knew nothing about the effects of UV radiation on plants (Nachtwey, Caldwell, and Biggs 1975). Therefore, one of our first needs was to estimate the degree of UV sensitivity that occurs in plants. To date, over 200 different plant species and varieties have been screened for their responsiveness to increased UV (Teramura 1983; Van and Garrard 1975; Van, Garrard, and West 1976; Tevini and Iwanzik 1982; Biggs and Kossuth 1978). Most of this work was done on crop plants but also a fair number of native plants and trees have been examined. Although this initial work was performed by numerous independent investigators under a wide array of experimental techniques, an alarming trend emerged: nearly two out of every three plants tested showed some degree of UV sensitivity (Teramura 1983; National Academy of Sciences 1982). Members of the pea and bean, squash and melon, and cabbage families are especially sensitive to UV damage (Teramura et al. 1983; Biggs and Kossuth 1978; Sisson 1981; Steinmuller 1986). A diverse array of UV responses can be seen in plants, including physiological and biochemical responses, as well as morphological and anatomical ones (Teramura 1983; Klein, Edsall, and Gentile 1965; Caldwell 1981; Tevini, Duansik, and Thomas 1981). In general UV radiation deleteriously affects plant growth reducing leaf size, limiting the area available for energy capture (Table 1). Plant stunting and a reduction in total dry weight are also typically seen in UV-irradiated plants. Of course this large degree of sensitivity elicited considerable concern; however, during the last five years it has been found that at least some of this sensitivity was directly attributable to the experimental growth conditions (Teramura 1982; Teramura, Biggs, and Kossuth 1980). In general, plants grown in growth chambers and greenhouses are much more susceptible to UV than plants grown outdoors. Although not fully understood, at least part of this is due to the incomplete development of some of the natural plant protective mechanisms against UV damage (Mirecki and Teramura 1984). Therefore it is necessary to examine whole plant responses in the field whenever possible. Unfortunately, due to the greater costs and complexities of field experiments, less than a dozen or so studies have been

Table 1. A Summary of the Effects of UV-B Radiation on Crop Growth

A. Physiological/biochemical effects

1. Photosynthesis
   - Hill reaction
   - Electron transport
   - RuBP carboxylase
   - PEP carboxylase
   - Dark respiration
   - Stomata
   - Photosynthetic pigments
2. Soluble proteins
3. Lipids
4. Carbohydrates
5. Non-photosynthetic pigments
6. Plant hormones

B. Morphological/anatomical effects

1. Leaf area
2. Specific leaf weight
3. Epidermal transmission
4. Bronzing/glazing/chlorosis
5. Seedling growth/stunting
6. Dry matter production/allocation
7. Yield

C. Response differences

1. Interspecific (species differences)
2. Intraspecific (cultivar differences)

D. Environmental interactions

1. Visible radiation (photoprotection)
2. Water stress

Source: Teramura (1983)

attempted (Teramura 1983). Currently there are only three ongoing field studies: two sponsored by the United States Environmental Protection Agency (EPA), and one European study is being sponsored by the West German Ministry for Research and Technology (BMFT).

While there is a need for field validations to examine whole plant responses, it is also essential to perform some key growth chamber studies to understand the underlying causes and mechanisms of UV damage. Otherwise we will have to blindly screen plants in the field. Controlled environment studies have provided us with insights into natural mechanisms that protect plants from UV (Beggs, Schneider-Ziebert, and Wellman 1986; Wellmann 1975). These protective mechanisms include a wide assortment of diverse biochemical and morphological adaptations that collectively suggest that UV radiation has been a strong selective force during the evolution of plants. For example, many plants produce UV-absorbing pigments in their upper leaf surfaces, preventing UV from penetrating into the leaf (Robberecht and Caldwell 1978; Robberecht, Caldwell, and Billings 1980; Wellmann 1982). This is somewhat analogous to suntanning in human skin. Yet despite these and other mechanisms against UV damage, some plants still appear to be sensitive to even current outdoor levels of UV radiation (Sisson and Caldwell 1976; Bogenrieder and Klein 1978).

Experimental evidence indicates that the effectiveness of UV radiation on plants is not necessarily linear and there is not always a one-to-one relationship between UV dose and damage. It is especially clear in field studies that UV effectiveness is modified by other environmental factors, including the pattern of precipitation, temperature during the growing season, soil fertility, and others (Murali and Teramura 1986). For example, under water stress or mineral deficiency, plants are less susceptible to UV injury (Murali and Teramura 1985). Therefore, the greatest UV damage is anticipated under well-fertilized, irrigated situations.

Although it is probably the most important issue concerning the general public, the effects of UV radiation on crop yield has only been examined in a handful of studies (Teramura 1983). In fact, detailed information only exists for one or two crops. Field studies at the University of Maryland (U.S.A.) have found that a 25% ozone depletion can result in up to a 20%-25% reduction in total soybean crop yield (Table 2). Additionally, UV radiation reduces seed quality, in terms of reduced seed protein and oils (Teramura unpublished data). This UV-induced reduction in yield is in addition to current losses from weeds, pests and diseases, insect attack, etc. Some preliminary evidence suggests that UV might also heighten losses in these other categories (Esser 1980), effectively producing even greater yield reductions. If these data for soybean are also generally applicable for other key crops, such as rice, wheat, or corn, then there is no doubt that we should be greatly concerned with the potential consequences of ozone depletion upon global food production.

In addition to direct effects on plants, UV radiation may also play a more subtle role by indirectly affecting the manner or degree by which plants interact with one another (Fox and Caldwell 1978; Gold and Caldwell 1983). A simple example of this might be seen in the competitive interaction between a crop plant and its associated weedy species. UV radiation may produce a

Table 2. Summary of UV Effects on Soybean Yield and Quality

Year	% change in yield	% change in seed quality	
		protein	oils
1981	-25	--	--
1982	-23	-5	-2
1983	+6	-4	+1
1984	-7	0	-2
1985	-20	0	0

Source: Teramura (unpublished)

subtle change, perhaps an increase in rooting depth of the weed, which may then allow the weed to outcompete the crop plant for water or nutrients. The net effect of such a change would be an increase in weediness and the associated problems. In a natural ecosystem, this weediness would lead to a proliferation of UV-tolerant organisms at the expense of UV-sensitive ones, which potentially means that the distribution of species may be quite different in a UV-enriched future.

Despite our increased knowledge of the biological effects of UV radiation, there is still an enormous amount of uncertainty concerning the consequences of ozone depletion (Table 3). For example, we know that there exists a tremendous diversity of responses among different plant species to UV radiation. Yet we still do not have a good understanding why these differences occur. Although over 200 species and varieties of plants have been screened for UV sensitivity, 90% of these were crop plants. Therefore, very little information exists on the impacts of UV on native terrestrial plant communities, which account for over 90% of the total productivity in the world (Table 4). Therefore, to address the larger question of the potential consequences of enhanced levels of UV-B radiation on global communities and ecosystems, we must currently make the unlikely assumption that perennial woody trees, such as oaks, respond in an analogous fashion as herbaceous annual agricultural species, such as spinach.

Although we recently have obtained some information on the effects of UV in combination with some other commonly experienced stresses, such as water stress and mineral deficiency, we have virtually no information on the effects of UV in combination with other atmospheric change, such as increased concentrations of ozone, sulfur dioxide, or carbon dioxide. Although UV radiation generally produces deleterious effects on plants, increased ambient levels of CO_2 have beneficial effects (Table 5); the combination of the two may not necessarily be compensatory. One alternative possibility is larger plants resulting from CO_2 enrichment, which in turn would still be deleteriously affected by UV radiation. Without experimental evidence, critical uncertainties such as this cannot presently be resolved.

Table 3. Current Uncertainties of UV Effects on Plants

- Action spectra
- Reasons for tolerance and sensitivity
- Effects on natural communities and ecosystems
- Combined effects with pollutants
- Effects in high ambient CO_2 environment

Table 4. Survey of UV Studies by Major Terrestrial Plant Ecosystems (after Whittaker 1975)

Ecosystem	Global NPP (10^9 ton/yr)	Total Area (10^6 km^2)	Included in UV Study 1/
Tropical forest	49.4	24.5	no
Temperate forest	14.9	12.0	yes
Savanna	13.5	15.0	no
Boreal forest	9.6	12.0	no
Agricultural	9.1	14.0	yes
Woodland and scrubland	6.0	8.5	no
Temperate grassland	5.4	9.0	yes
Swamp and marsh	4.0	2.0	no
Desert and semidesert	1.7	42.0	no
Tundra and alpine	1.1	8.0	yes

1/ Only studies examining some aspect of growth.

Table 5. Summary of UV-B and CO_2 Effects on Plants

Plant Characteristic	Enhanced UV-B	Doubling of CO_2
Photosynthesis	Decreases in many C_3 and C_4 plants	In C_3 plants increase up to 100% but in C4 plant only a small increase
Leaf conductance	No effect in many plants	Decreases both in C_3 and C_4 plants
Water use efficiency	Decreases in most plants	Increases in both C_3 and C_4 plants
Dry matter production and yield	Decreases in many plants	In C_3 plants almost doubles but in C_4 plants only a small increase
Leaf area	Decreases in many plants	Increases more in C_3 than in C_4 plants
Specific leaf weight	Increases in many plants	Increases
Crop maturity	No effect	Accelerated
Flowering	May inhibit or stimulate flowering in some plants	Flowers produced earlier
Interspecific differences	Species may vary in degree of response	Major differences occur between C_3 and C_4 plants
Intraspecific differences	Response varies among cultivars	Response may vary among cultivars
Drought stress	Plants become less sensitive to UV-B but not tolerant to drought	Plants become more drought tolerant

Source: Lemon (1983); Teramura (1983)

In summary, we know that large differences exist among species and these are manifested in a diverse array of physiological, biochemical, and morphological responses. We know that for whole plant responses, field validation experiments are essential because plants are more sensitive to UV when grown indoors. Key growth chamber studies are necessary to provide an understanding of the mechanisms of UV sensitivity in plants. UV effectiveness can be modified by the prevailing microenvironment. For example, water stress can completely mask any UV effects seen in the field. Moderately large ozone depletions can reduce crop yields in the field. UV can produce subtle shifts that alter the competitive balance among plants.

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The Effect of Solar UV-B Radiation on Aquatic Systems: An Overview

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ABSTRACT

Various experiments have demonstrated that UV-B radiation causes damage to fish larvae and juveniles, shrimp larvae, crab larvae, copepods, and plants essential to the aquatic food web. These damaging effects include decreases in fecundity, growth, survival, and other functions of these organisms. In natural marine plant communities a change in species composition rather than a decrease in net production would probably result of enhanced UV-B exposure. The change in community composition could result in a more unstable ecosystem and would be likely to have an influence on higher trophic levels. A decrease in column ozone would diminish the near-surface season of invertebrate zooplankton populations. Whether the population could endure a significant shortening of the surface season is unknown.

The direct effect of UV-B radiation on food-fish larvae closely parallels the effect on invertebrate zooplankton. Information is required on seasonal abundances and vertical distributions of fish larvae, vertical mixing, and penetration of UV-B radiation into appropriate water columns before effects of incident or increased levels of exposure to UV-B radiation can be predicted. However, in one study involving anchovy larvae a 20 percent increase in incident biologically damaging UV-B radiation (a result of about a 9 percent decrease in the atmospheric ozone column) would result in all the larvae within a ten-meter mixed layer in April and August being killed after fifteen days. It was calculated that about 8 percent of the annual larval population throughout the entire water column would be directly killed by a 9 percent decrease in column ozone.

INTRODUCTION

Aquatic environments include shallow freshwater ponds, lakes and streams, fresh and saline inland seas, brackish-water marshes, swamps and estuaries, and a wide variety of marine habitats. The marine habitats extend from

inshore coastal regions, surf zones, and fringing reefs to the wide spaces of the open sea and the abyssal deeps. Inland waters cover less than 1 percent of the earth's surface, while the oceans extend over more than 70 percent of the earth's surface.

Because of the relatively small volume of inland waters, freshwater plant production contributes only a few percent to the total global productivity (Table 1). Marine systems, covering a vast area, contribute significantly to global productivity--an amount equivalent to half the terrestrial plant production. The coastal kelp forests have productivities said to rival those of tropical rain forests, generally considered the world's most productive plant ecosystems (Mann 1973; Lieth 1975). Of the five major marine habitats considered in Table 1, the microscopic plants of the open sea are the most productive, contributing 75 percent of the marine primary production, 24 percent of the global total.

Photosynthesis, the conversion of radiant energy from the sun into chemical energy (food), is the basis of almost all life on the earth. Photosynthesis requires light, but adequate sunlight seldom penetrates to the bottom of natural waters; thus, aquatic photosynthesis is largely confined to a relatively thin layer at the water surface termed the euphotic zone, the surface layer where plants create more chemical energy by photosynthesis than they use for their own metabolism.

Organisms in fresh water or the oceans are either swimmers (nekton), bottom-dwellers (benthos), or drifters (plankton). Plankton can be either plants (phytoplankton) or animals (zooplankton). An important zooplankton group, the icthyoplankton, is comprised of the drifting eggs and larvae of many species of fish. Zooplankton in general contain nearly all groups of aquatic animals, at least for some phase in their life history, such as the egg and/or larval stage. Zooplankton are found at all depths, depending on species and season, but are most abundant in the upper 100 m sunlit where the bulk of their food, including phytoplankton, is found. As feeding progresses from the phytoplankton through the zooplankton to fish and other higher organisms (the food web), the chemical energy generated by aquatic photosynthesis becomes more and more concentrated into organisms of larger size, reaching organisms suitable for harvesting for human use.

Marine ecosystems are highly dynamic and of bewildering complexity. Many of the fundamental processes affecting the abundance of marine resource stocks are poorly understood. For example, the complexity of food webs in the ocean appears to be much greater than for terrestrial populations (Larkin 1978). Little is known in a quantitative sense about marine ecosystems, although some geographical areas are currently under intensive investigations.

Many other sources of complexity in marine population dynamics exist. Simple density-dependence mechanisms, for example, can theoretically result in so-called "chaotic" oscillations in population abundance (Levin and Goodyear 1980). Most fish stocks undergo significant irregular fluctuations, the underlying causes of which are not well understood. In most cases both density-dependent and density-independent effects are probably involved.

For any given level of fish mortality, the productivity or equilibrium yield of a stock depends upon growth, recruitment, and natural mortality.

Table 1. Representative Primary Production and Plant Biomass Summaries of the Earth (adapted from Whittaker and Likens 1975)

Ecosystem Type	Area (millions of square kilometers)	Net Primary Productivity (grams per square meter per year)	Mean Plant Biomass (kilograms per square meter)
TERRESTRIAL			
Tropical rainforest	17.0	2200	45.0
Tropical seasonal forest	7.5	1600	35.0
Temperate evergreen	5.0	1300	35.0
Temperate deciduous	7.0	1200	30.0
Boreal forest	12.0	800	20.0
Woodland and shrubland	8.5	700	6.0
Savannah	15.0	900	4.0
Temperate grassland	9.0	600	1.6
Tundra and alpine	8.0	140	0.6
Desert and semi-desert scrub	18.0	90	0.7
Extreme desert, rock, sand and ice	24.0	3	0.02
Cultivated land	14.0	650	1.0
Swamp and marsh	2.0	2000	15.0
Lake and stream	2.0	250	0.02
Total/Average	149	773	12.3
Percent of Worldwide	29%	68%	99.8%
MARINE			
Open ocean	332.0	125	0.003
Upswelling zones	0.4	500	0.02
Continental shelf	26.6	360	0.01
Algal beds and reefs	0.6	2500	2.0
Estuaries (excluding marsh)	1.4	1500	1.0
Total/Average	361	152	0.01
Percent of Worldwide	71%	32%	0.2%
WORLD TOTALS/AVERAGES	510	333	3.6

Growth is relatively easy to measure and understand; recruitment is relatively easy to measure but difficult to understand; and natural mortality is both difficult to measure and difficult to understand. The phenomena that are difficult to measure or understand are usually masked by the standard productivity analysis.

As early as 1925, scientists were aware of the damaging effects from the ultraviolet component of sunlight even on aquatic organisms (Huntsman 1925; Klugh 1929, 1930; Harvey 1930; ZoBell and McEwen 1935; Giese 1938; Bell and Hoar 1950; Dunbar 1959; Marinaro and Bernard 1966). It was shown at these early dates that different species have various sensitivities to UV radiation, and that this differential sensitivity might relate to the depth at which the species were found.

There have been several more recent studies on the effects of UV-B radiation on a variety of marine organisms (NAS 1979; NAS 1984). Regardless of species investigated, each study has potential importance through the role of the particular organism in its environmental or food web context. Some studies, in addition, have considered economically important zooplankton species, such as larval stages of certain shrimp, crab, and fish. Recent literature reviews (Calkins 1982; Worrest 1982, 1983a,b) have summarized the results of most of these studies.

Physical Effects on Organisms

UV-B radiation is readily absorbed by proteins and nucleic acids, and is effective in inducing photochemical reactions in plants and animals (Caldwell 1971; Murphy 1975; Giese 1976). Even though proteins and nucleic acids are commonly involved in biological responses to UV-B radiation, the action spectra for tissue damage in many organisms may differ because of wavelength-dependent refraction, reflection, or absorption, and hence protection, by outer tissues (Cheng, Douek, and Goring 1978).

The usual effects of environmental stress (e.g., pollution) are changes in overall productivity and reduction in species diversity. Diversity is associated with stability in ecosystems, allowing alternate routes and choices within food webs. In field situations under slight stress one often cannot measure changes in productivity or size of specific populations, but sometimes changes in species diversity can indicate that adverse effects are occurring. With loss of species an ecosystem loses some of its natural resiliency and flexibility. In aquatic ecosystems we must consider a great number of species with different life stages and different trophic levels. With increased knowledge of ecosystems and the physical and chemical environments, the effects of enhanced solar UV radiation on single species could be placed in perspective.

As already noted, the biological response to ultraviolet radiation can be very wavelength-dependent. This wavelength specificity makes it necessary to develop weighting functions to express ultraviolet radiation in biologically meaningful terms. Biological action spectra normally serve as the basis for these weighting functions. The weighting function is normally taken as an action spectrum for a particular response. Several action spectra have been developed describing the response of biological systems to UV-B radiation (Caldwell et al. 1986). Examples are a representation of DNA response (Setlow 1974), and a generalized plant response (Caldwell 1968).

Based on an analytic characterization of ultraviolet sun- and skylight, a 10 percent ozone reduction at 45°N latitude would result in only a 1 percent increase in total solar ultraviolet (290-360 nanometers) daily exposure at the surface of the earth. This would be of minimal consequence if radiation throughout the solar spectrum were of equal biological effectiveness. However, when the biological weighting functions based on the action spectra are employed, a very different picture emerges. Based on DNA damage, a 10 percent ozone reduction would result in a 28 percent increase in biologically effective radiation (Table 2). The generalized plant response (damage) would increase by 21 percent.

Table 2. Relationship Between Ozone Depletion and Biological Effectiveness of Increased UV-B Radiation.

Ozone Decrease	Increase in UV Radiation 290-320 nm	290-320 nm	Increase in Effectiveness[a] DNA	Plant
10%	8%	1.1%	28%	21%
20%	17%	2.4%	67%	49%
30%	27%	3.7%	125%	85%
40%	38%	5.2%	213%	132%

[a]Action spectra are referenced to 300 nm = 1.00.

The increased exposure to biologically effective (DNA, plant) ultraviolet radiation resulting from a 10 percent decrease in stratospheric ozone would correspond to migrating over 30° toward the equator--a change of ecological significance. Levels of UV-B irradiance vary latitudinally, with the highest exposures in the tropics. The current difference between the extremes of exposures is about three- to sixfold but biota are presently adapted to the levels that are normally experienced at their current locations.

There is increasing evidence that marine ecosystems change as a result of natural as well as events induced by human activities. Many of these changes occur on time scales of tens of years. The past changes may be associated, in some general context, with gradual climatic trends, but ecological changes seem to occur quite rapidly, with relatively persistent communities existing in the intervening periods. In any region, rather than having one ecosystem, there are two, or possibly several, alternatives--each resilient to some range of variability but capable of being replaced if some factors in the environment pass a threshold. To this natural episodic response we must now add the effects of anthropogenic perturbations. The evidence suggests that we will continue to have such changes but will have additional questions of attributing cause to natural stresses or to stresses resulting from human activities. Although we may not be able to predict when, or possibly why, such changes occur, they can be regarded as alternative ecological solutions. Once again, whether we consider these changes deleterious or beneficial is a matter of human values, but we must keep in mind that these problems are occurring on a global scale.

Phytoplankton

The amount of UV-B radiation reaching the ocean's surface has long been suspected as a factor influencing primary production. Research shows convincingly that ultraviolet radiation, at levels currently incident at the surface of natural bodies of water, has such an influence (Steemann Nielsen 1964; Jitts, Morel, and Saijo 1976; Hobson and Hartley 1983). It has been calculated that near the surface of the ocean, enhanced UV-B radiation simulating a 25 percent reduction in ozone concentration would cause a decrease in primary productivity of about 35 percent (Smith et al. 1980); the estimated reduction in production for the whole euphotic zone would be about 10%. These calculations are based on attenuation lengths, i.e., the product

of depth in the water column and the diffuse attenuation coefficient of the water. Therefore, waters of various turbidities and absorption characteristics can be compared.

Effects induced by solar UV-B radiation have been measured to depths of more than twenty meters in clear waters and more than five meters in unclear waters. The euphotic zone (i.e., those depths with light levels sufficient for net photosynthesis to be positive) is frequently taken as the water column down to the depth to which 1 percent of the surface photosynthetically active radiation penetrates (Figure 1). In marine ecosystems, UV-B radiation penetrates approximately 10 percent of the upper marine euphotic zone before it is reduced to 1 percent of its surface irradiance (Figure 2). Penetration of UV-B radiation into natural waters is a key variable in assessing the potential impact of this radiation on any aquatic ecosystem.

If one assumes that present phytoplankton populations sense and control their average vertical position in such a way as to limit UV-B exposure to a tolerable level, then a 10 percent increase in solar UV-B radiation would necessitate a downward movement of the average position sufficient to reduce the average UV-B exposure by 10 percent. There would be a corresponding reduction of light for photosynthesis; the loss of photosynthetically active radiation is the primary limiting factor for marine productivity (Russell-Hunter 1970). The loss of photosynthetically active radiation from optical measurements has been estimated to be in the range of 2.5 to 5 percent for a 10 percent increase in UV-B radiation (Calkins, Volume 2). If the photosynthetic base of aquatic ecosystems were perturbed one would expect ramifications to extend up through the food web through predator-prey relationships.

Experiments with marine diatoms have shown significant reductions in biomass, protein, and chlorophyll at UV-B irradiances equivalent to ozone reductions ranging from 5 to 15 percent In addition, studies on chain-forming diatoms and other phytoplankton in the laboratory showed that increased growth occurs when the UV-B radiation is filtered out of the incident solar radiation, indicating that existing levels of UV-B radiation depress productivity (Thomson, Worrest, and Van Dyke 1980; Worrest 1982). Furthermore, indirect effects of ambient levels of UV-B radiation endanger the survival of microorganisms (Euglena, slime mold, some blue-green algae) by decreasing their motility and by inhibiting phototactic and photophobic response (Haeder, see Volume 2). This reduces the ability of a population to move into favorable environments, which would result in damage that may impair development.

Direct measurements of photosynthesis that span a single day could underestimate the overall action of solar UV exposure by failing to account for the next day's population level. Growth delay or direct killing may cause the subsequent population to fall below the numbers that an unexposed population would attain. Prolonged delays (about two days) in growth of the survivors have been observed when two strains of the diatom Thalassiosira were irradiated with simulated solar UV-B radiation at doses below lethal levels. If unicellular organisms are in a rapid growth phase, a growth delay equaling the time of one growth cycle produces the same effect on the subsequent population as would be produced by 50 percent killing (without growth delay).

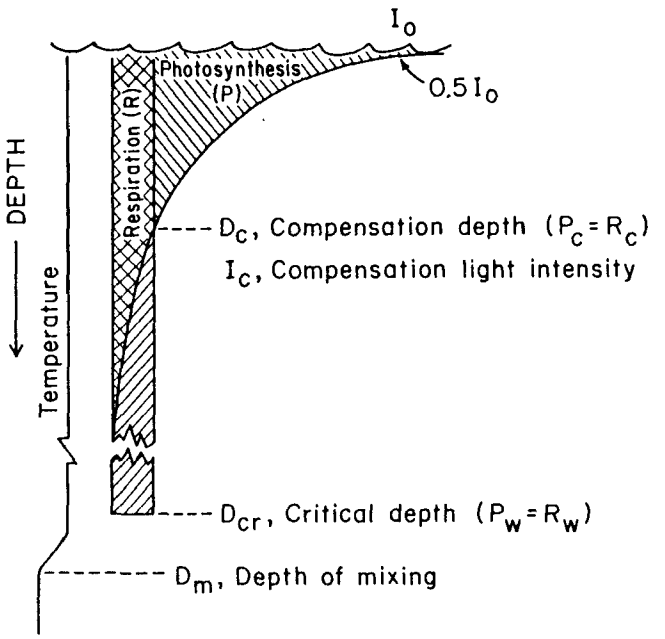

Figure 1. The Relationship Between the Compensation Depth or Euphotic Depth, the Critical Depth, and the Depth of Mixing

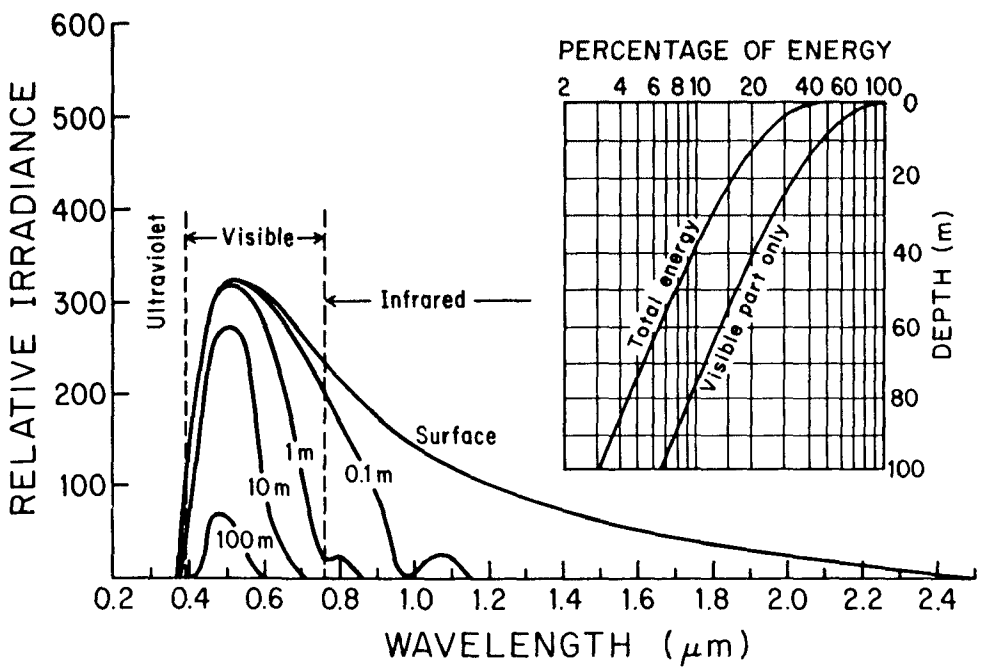

Figure 2. Solar spectral irradiance at the surface of the ocean and at four depths (adapted from Sverdrup et al. 1942). Insert illustrates percentage of energy transmitted at depth in oceanic waters.

In Hawaii, long-term photoinhibition of growth of six algal species under natural sunlight was measured by Jokiel and York (1984). Two strains could not grow at all at the levels of irradiance for full natural surface sunlight. Of the species tested, those collected from tropical surface water showed the greatest adaptive power, but it is reasonable to conclude that resistance to solar UV radiation is achieved through expenditure of resources that can be better applied to other needs in less-exposed species.

In simulated marine ecosystems, enhanced UV-B radiation levels, simulating 15 percent decreases in ozone, result in shifts of the species diversity and community composition of phytoplankton communities (Worrest, Thomson, and Van Dyke 1981). It appears that in natural communities a change in species composition rather than a decrease in net production might be a more likely result of an enhanced UV-B exposure. The decreased species diversity observed in simulated field studies is usually not accompanied by deleterious effects on biomass and chlorophyll accumulation or by deleterious effects on total community primary productivity. However, a change in community composition might result in a more unstable ecosystem and might have influence on higher trophic levels (Kelly, Volume 2). One effect of enhanced levels of UV-B radiation would be to alter the size distribution of the component producers in a marine ecosystem. Increasing or decreasing the size of the representative primary producers upon which consumers graze can significantly increase the energy allotment required for consumption, thereby reducing the feeding efficiency of the consumer. In addition, the food quality of the producers is altered by exposure to UV-B radiation. It has been demonstrated that the protein content, dry weight, and pigment concentration are all depressed by enhanced levels of UV-B radiation.

Zooplankton

Zooplankton are critical components in typical aquatic food webs (nutrient pathways) that lead to larger animals, including those comprising commercial fisheries (finfish and shellfish) and therefore humanity itself. With respect to potential impacts of enhanced solar UV-B radiation, only the zooplankton living in daylight in the upper several meters would be directly affected. Many zooplankton species normally live very close to the surface, even in daylight, while others occupy the near-surface layer during only part of their life cycle.

The near-surface layer is a very important zone in the interactions of the physical, chemical, and biological components of aquatic systems. Zooplankton have apparently evolved mechanisms and behavior by which they have adjusted to current levels of UV radiation (Damkaer 1982), but they may not be able to adjust to relatively rapid increases. If there were changes in the abundance of zooplankton species, those changes would have an impact far beyond any direct effects because of the critical role of zooplankton in energy transfer within the ecosystem.

Karanas, Van Dyke, and Worrest (1979, 1981) presented evidence that acute exposure of a marine invertebrate zooplankton resulted in reduced survival of the organisms. They also showed that exposure of this species to sublethal exposures of UV-B radiation could also reduce the fecundity of the parents. Thomson (Volume 2) demonstrates that current levels of UV-B radiation are of significance in the developmental life of several species of shellfish. For

some species, a 10 percent decrease in column ozone could lead to as much as an 18 percent increase in the number of abnormal larvae produced.

Spawning of zooplankton (and fish) is usually timed so that survival at hatching is optimized. Compared to birds and mammals, the lack of internal temperature control, such as prevails in most aquatic animals, makes ambient temperature exert overriding and continuous accelerating or decelerating influences on metabolic functions and, hence, on the growth of aquatic animals at whatever stage.

Before feeding by zooplankton can begin, variations in exposure to UV-B radiation may cause stresses at various stages of egg and very early larval development, causing mass mortalities or an alteration in time of occurrence at the surface. The matching in time of the onset of larval feeding and the spring phytoplankton bloom--which, in turn, depends on climatic events for its timely occurrence--will, in fact, determine the sizes of year classes of grazers (Cushing 1972).

Fish stocks suffer most from the vagaries of climate through the effects that changes in ambient conditions have on the larvae. The biological dynamics at the larval stages in the life cycles of fishes and aquatic invertebrates have a short time horizon and are highly variable. Instant mortality coefficients during the larval stages range between 300 and 400, while they are 0.2 to 1.5 in the juvenile and adult stages (Rothschild 1981). The most catastrophic and frequent event that can befall larvae is a mismatch in time between their food needs and the prevalence of their food (Cushing 1972). Larval stages last only a few days. Small as the biomass of fishes is during very early life, their future numbers are largely determined then and not later in life, when the biomass is large and when the commercial fishery takes its toll.

Regardless of the cellular-level responses to UV irradiation, it is usually noted that up to some level of UV exposure there is no apparent effect on the organism (Damkaer et al. 1980; Damkaer and Dey 1982). At greater doses either the repair systems themselves may become inactivated by the radiation or the damage to the general tissues goes beyond the capacity of the repair systems (Damkaer and Dey 1983). For such impacts to occur these threshold levels probably must be exceeded during several consecutive days. The apparent thresholds are near current levels. The thresholds for all groups in one test appeared to be above the present median solar incident UV levels at the test location, at least until late in the time span of natural occurrence near the surface (Damkaer, personal communication). This season could be significantly shortened by a 20 percent ozone reduction. Whether or not the populations could endure with a drastically reduced time of near-surface occurrence is not known. Success of any year-class depends on the timing of a great number of other events in addition to levels of exposure to UV-B radiation (Hunter, Kaupp, and Taylor 1982).

It has been thought that the superabundance of eggs spawned by most marine organisms make egg production an irrelevant factor in population control. The superabundance of marine eggs, however, is of clear evolutionary significance and must interrelate with the variability of population size.

The superabundance of eggs could have any number of purposes. First, it could satiate predators, thus enabling a certain fraction of eggs and larvae to slip through the predatory network. It could also maintain ecosystem integrity and metabolism by directly serving as food for other organisms or by being degraded into various essential nutrients, sustain cannibalistic species, or contribute to a patchy distribution of organisms, which is apparently essential to marine ecosystem structure.

As fish stocks decline in size, the biomass of eggs decreases at a faster rate than recruitment; the ordinary functions of the superabundance of eggs become stressed and modified. But stocks compensate to some extent for biomass decline by growing faster, tending toward an earlier maturity, and increasing in fecundity.

Hunter, Kaupp, and Taylor (1982) exposed anchovy eggs and larvae and mackeral larvae to high doses of UV-B radiation in small closed containers. These authors provided data that indicated that anchovy larvae off southern California are typically centered in moderately productive ocean water. Baker, Smith and Green (1981) calculated surface DNA-effective UV-B irradiance levels expected for this area, and Smith and Baker (1979) calculated the penetration of UV-B radiation into the moderately productive ocean water. An analysis of Damkaer (personal communication) indicates that 14.7 percent of the anchovy larvae would die in four to ten days if there were no vertical mixing of the larvae. These static situations no doubt approach "worst case" scenarios. However, static situations are not likely because of physical vertical mixing of water (through the action of wind, density currents, and tides) and the active and passive movement of fish larvae. If some vertical mixing did not offer relief from the effects of UV-B radiation, it is likely that even today there would be no anchovy larvae above a few meters depth, which is clearly not the case. The surface mixed layer probably extends to a depth of at least twenty-five meters from December to February (Sverdrup, Johnson, and Fleming 1942). A mixed layer of at least ten meters can be assumed for the rest of the year.

For the mixed situation in February, the larvae would spend less than one hour each day in the upper one meter, resulting in exposures where the threshold doses would never be reached in the larval stage. In the February model, with mixing to twenty meters, there would have to be a sixfold increase in incident UV-B radiation before threshold doses would be reached. For the months from March to October, with mixing to ten meters, the threshold doses are also not reached within the twenty days available before the larvae become vertically migrating. Only with the highest surface irradiances of April and August are these doses approached within this available time (about twenty-two days).

From March to October, with ten-meter mixing and a 20 percent increase in incident UV-B radiation (a result of about a 9 percent decrease in the atmospheric ozone column) the depth of the threshold dose-rate is increased. With the 20% increase in incident irradiance for the dose/dose-rate threshold model, all of the anchovy larvae within the ten-meter mixed layer in April and August would be killed, the threshold doses being achieved after fifteen days.

Apparently at all months about 36 percent of the larval anchovy population is less than ten meters deep (Hunter, Kaupp, and Taylor 1981). The

greatest numbers of anchovy larvae are found below the surface in April. (20 percent of annual population), so that 7.2 percent of the annual population would be eliminated with a 9 percent ozone decrease. Only 1.9 percent of the annual population is present in August, so the loss of those less than ten meters deep would amount to 0.7 percent of the annual population. The total predicted loss, then, due to a 9 percent decrease in total ozone column, would be about 8 percent of the larval anchovy population (Figure 3).

Because of complex interactions between mixing depths, vertical distribution of larval anchovy, seasonal changes in solar irradiance and the penetration of UV radiation into seawater, and seasonal changes in anchovy abundance, there is no linear relationship between mixing depth and predicted annual loss of anchovy larvae.

In addition to the direct effects upon the fisheries, it is possible that with less primary production of organic biomass there would also be an increased mortality in larval fish due to food limitation. And perhaps there would be a synergistic effect on mortality in that some animals could die from direct exposure, some from lack of food, and some from the combination of a reduction in food and the weakening from exposure (or could be weakened and be out-competed by other fauna for limited food reserves).

The impact on marine fisheries as a food supply to humans would be significant if the species of phyto- and zooplankton that adapted to enhanced levels of UV-B radiation were of different nutritional value (if they altered growth and fecundity of the consumers). If the indirect impact of suppression upon consumers were linear, a 5 percent reduction of primary production would result in a 5 percent reduction in fish production. A question still under investigation is whether these relationships might be nonlinear. For example, there may be an amplification factor involved that results in a relatively greater impact at higher trophic levels than at the primary producer level. As illustrated in Table 3, a 5 percent reduction in primary production (P1) would give an annual yield of 115 million metric tons of fish flesh (a 5 percent reduction), whereas a 5% reduction in the ecological efficiency of energy transfer (e) would yield 103 million tons of fish flesh (a 14 percent reduction).

Potential Consequences to World Fisheries

Well over 95 percent of the sea's living resources occur within belts of ocean two hundred miles wide, surrounding the coastal nations of the world. By international agreement each nation exercises economic jurisdiction over these Extended Economic Zones (EEZs). With the establishment of the two hundred-mile EEZs, the coastal nations of the world have acquired an area of sea surface amounting to about 25 percent of the globe. More than 99 percent of the global catch of marine fisheries is currently taken within the EEZs. These fish are of crucial importance in world nutrition, making up about 18 percent of the average world animal protein intake. That figure rises to nearly 40 percent in Asia where more than half of the world's population lives. The people of Japan, for instance, derive about 60 percent of their intake of animal protein from the ocean (Clark 1981). The annual income to the world's fishermen from marine catches is roughly US$10 billion, with a world fish catch of about seventy million metric tons.

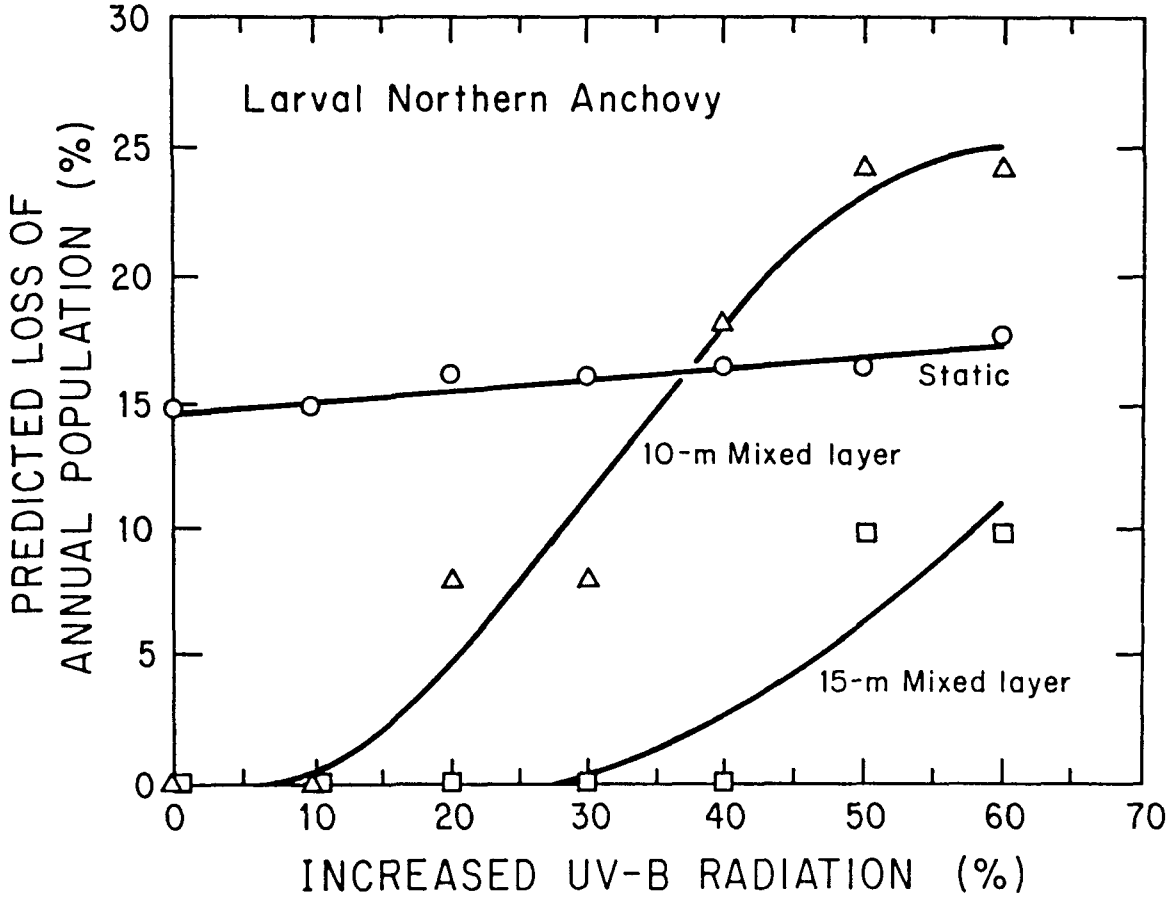

Figure 3. Effect of increased levels of solar UV-B radiation on the predicted loss of larval Northern Anchovy from annual populations, considering the dose/dose-rate threshold and the vertical mixing models (based on data of Hunter, Kaupp, and Taylor 1981, 1982).

Table 3. Annual fish production in coastal waters and impacts of 5 percent reductions in primary production and ecological efficiency of energy transfer. Baseline data for coastal waters adapted from Ryther (1960).

	Baseline	-5% P1	-5% e
Primary production, kJ/m^2yr	4200	4000	4200
Ecological efficiency per trophic level, (e)	0.15	0.15	0.14
Number of trophic levels from plant production to fish production, (n)	3	3	3
Fish production, $kJ\ m^2yr$	14	13	12
Total fish production, millions of metric tons per year (using Winberg's transformation, 4.2 kJ = 1 g fish flesh)	121	115	103
Percentage of baseline fish production	(100%)	(95%)	(86%)

To address the economic impact of enhanced levels of UV-B radiation on global fisheries the principal concepts that need to be considered are supply, demand, and the economic marketplace. Supply is the relationship between the quantity of a commodity that will be produced and the price of the output. For fish, the supply curve is heavily dependent on the biological productivity of the stock as well as economic factors, because supply is derived from the average cost required to produce a pound of fish. Supply is also affected by the fish or uncertainty associated with the various costs or availability of the raw material or other economic components of the supply curve. Demand is the relationship between the price consumers are willing to pay for a commodity and the quantity of the commodity that is available. Global production of fish has been predicted to be 92.5 million tons in the year 2000 (Robinson 1979). Based on per capita consumption of fish and population growth, the projected global demand for fish in the year 2000 will be 97.1 million tons. The economic marketplace is the abstract setting where producer interests in the form of the supply curve are brought together with consumer interests in the form of the demand curve.

The Peruvian anchoveta fishery is an example of the economic impact resulting from a stress on a fishery. The fishery developed in the 1960s into the world's largest single fishery. Since the export of anchoveta fishmeal constituted Peru's second largest source of foreign exchange, the loss of the fishery had a major influence on the Peruvian economy.

In 1970, Peru's anchovy harvest amounted to 12.3 million metric tons, more than 20 percent of the total world marine finfish catch for that year. These fish rely on phytoplankton blooms that result from the surfacing of colder nutrient-rich water. In 1972, the Peruvian catch plummeted to 4

million metric tons and fell further in 1973 to 1.8 million metric tons. The primary cause of this drastic collapse was the occurrence of an El Nino, although heavy fishing aggravated the condition (Bardach and Santerre 1981). The economic consequences to the fishery were catastrophic. The major use of the anchoveta harvest was for the production of fishmeal, which was used as a major source of bulk protein in livestock feed. A shortfall of the fishmeal in the world's markets had severe ripple effects on other animal feeds and on livestock prices. The price of fishmeal rose 127 percent, the price of soybean meal rose 99 percent, and the cost of pork, for example, rose 96 percent, adjusted for inflation.

The recovery of a depleted fishery population may require many years, even if catches are prohibited. Economic survival of the existing resource industry may, however, depend upon continuing catches, even though these will delay rebuilding of the stock and perhaps increase the probability of the population's collapse. In the language of the mathematical theory of games, common-property resource exploitation has the characteristics of the prisoner's dilemma.

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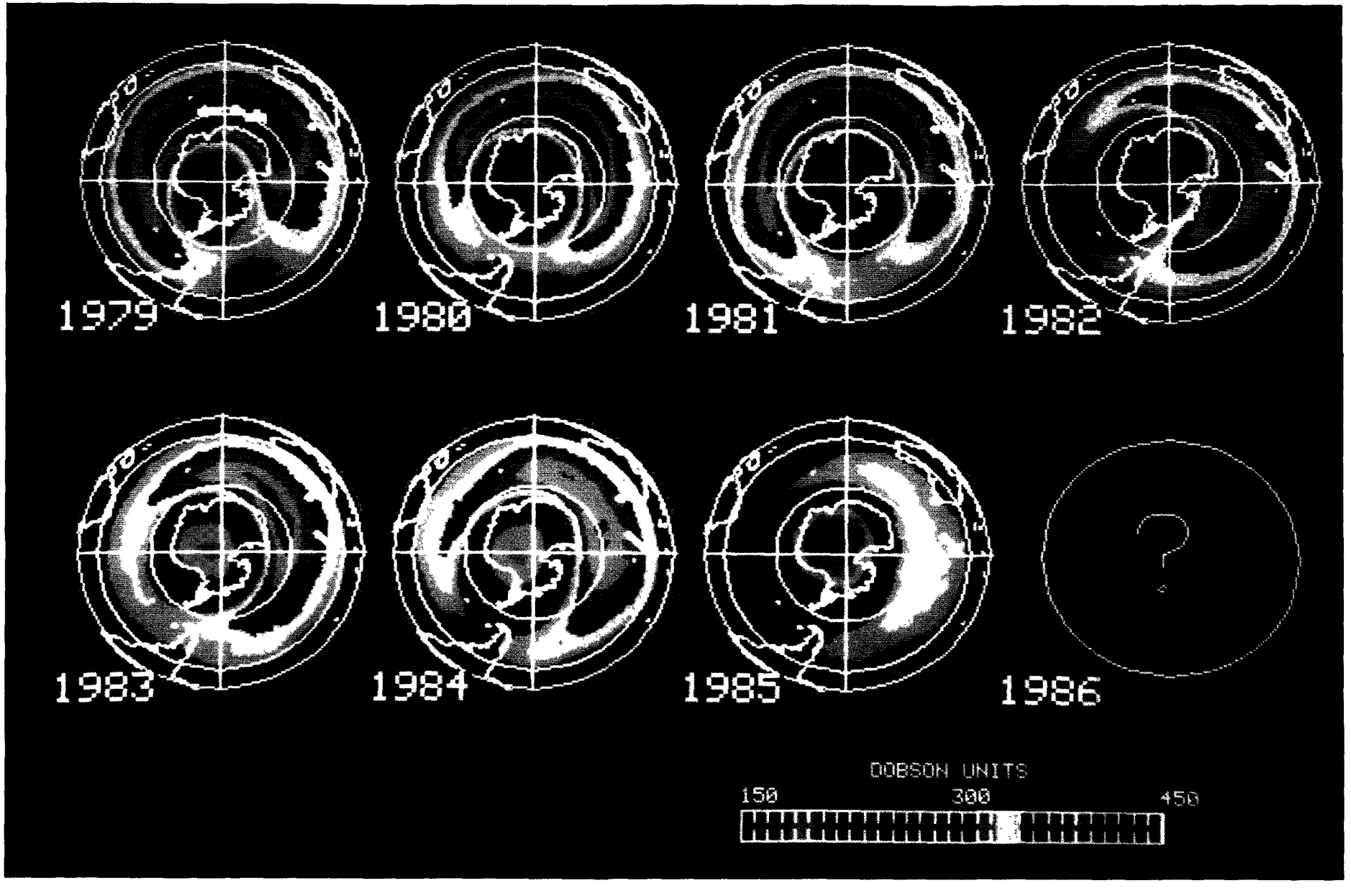


Plate 1. Decline of Ozone Concentrations in October Over Antarctica

Mean concentrations of ozone in the month of October declined more than 40 percent over Antarctica from 1979 to 1985. The southern tips of Chile and Argentina also show declines. A Dobson unit is equivalent to 0.01 millimeters of ozone at standard atmospheric pressure; the average ozone column of 300 Dobson units thus represents a layer 3 millimeters thick.

Source: Watson (this volume)

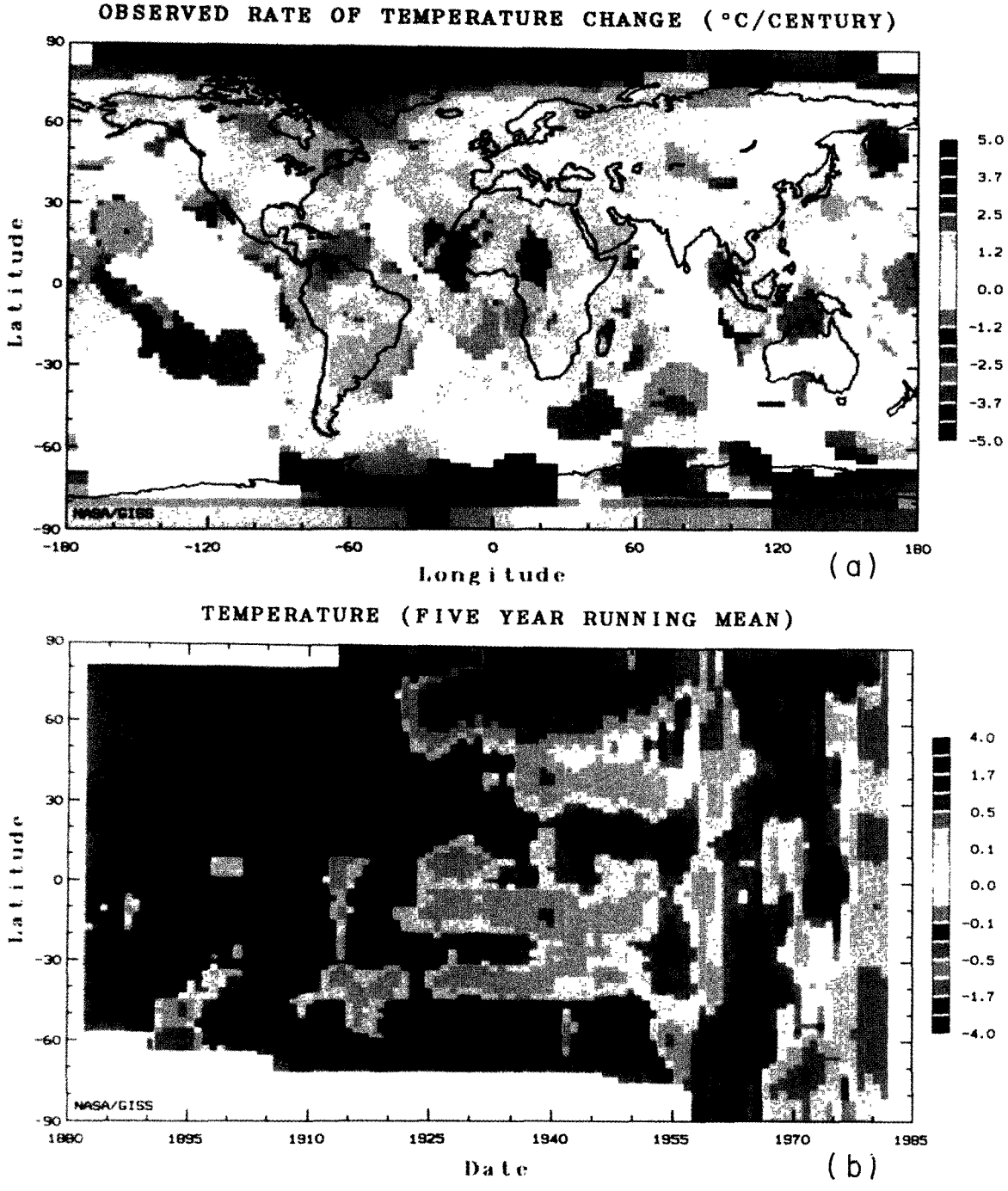
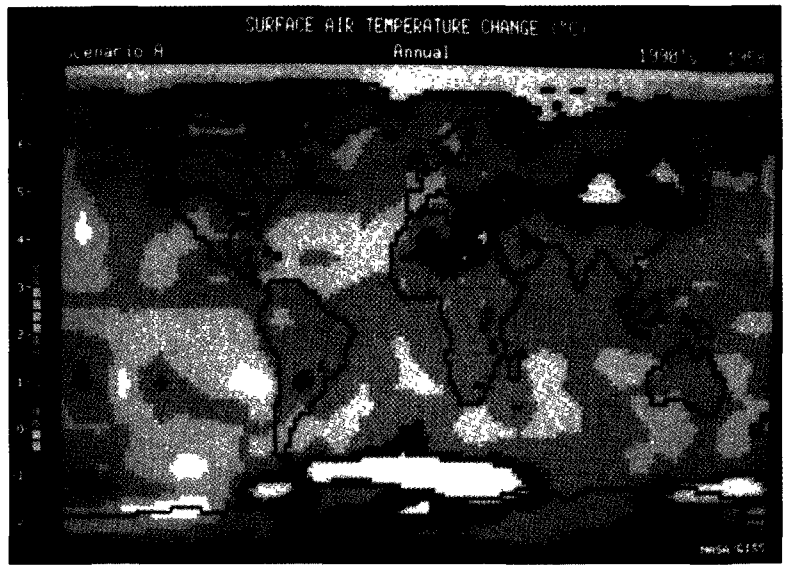


Plate 2. Observed rate of temperature change in the past century, estimated from meteorological station data. The geographical temperature trends in part (a) include estimates for remote regions with station records as short as 25 years. The zonal mean trends in part (b) refer to the average for all longitudes with available records. A nonlinear scale is used in part (b) so that there is a similar area for each color.

Source: Hansen et al. (this volume)



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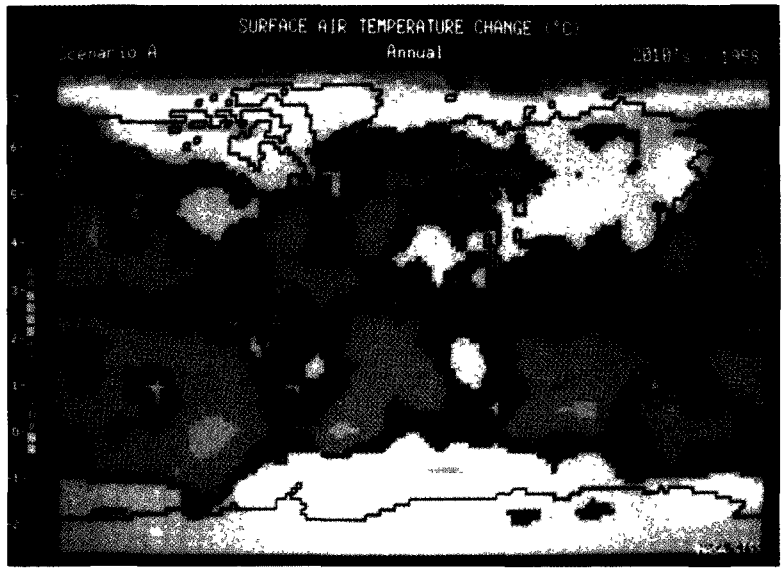

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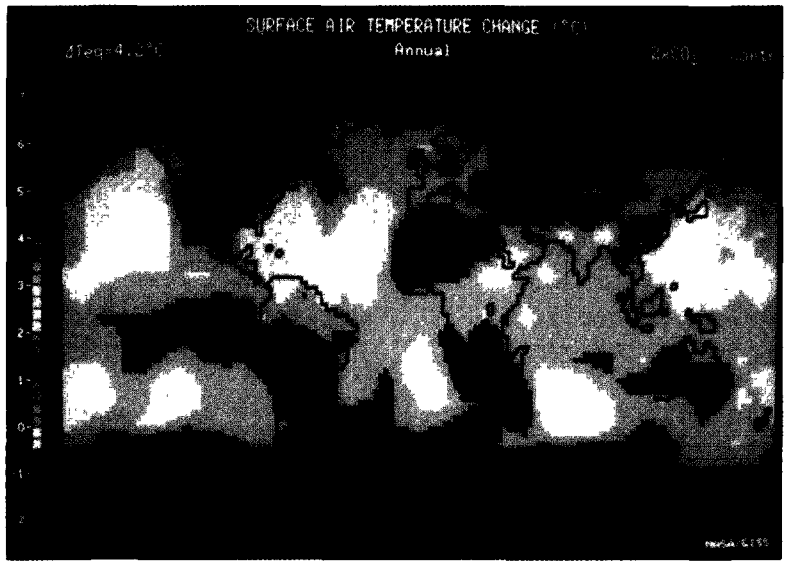

c

Plate 3. Annual mean temperature changes computed with the Goddard Institute for Space Studies global climate model, which has a sensitivity of about 4°C for doubled CO_2. Parts a and b, for the decades 1990-1999 and 2010-2019, respectively, were obtained from the transient experiment with CO_2 and trace gases increasing according to Scenario A; the indicated temperatures are the difference between the transient run and a control run with 1958 atmospheric composition. Part c is the equilibrium warming in the model for doubled CO_2.

Source: Hansen et al. (this volume)

Legend:

Black	- rivers
Red	- forest cover; transplanted aman/fallow
Orange	- deepwater aman rice/boro rice
Blue	- water
White	- aman rice/fallow
Grey	- deepwater rice/urban area (Dacca)

Plate 4. The high scenario represents the shoreline retreat from a 2 to 2.5 meter global rise in sea level if dams built on the Ganges prevent sediment from reaching the delta. The low scenario represents the impact of a 50 centimeter global rise with only a partial disruption of the sedimentation process.

Source: Broadus et al. Volume 4

CLIMATE CHANGE

The Greenhouse Effect: Projections of Global Climate Change

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S. Lebedeff[3], R. Ruedy[3], and P. Stone[4]

SUMMARY

We present projections of global climate during the next several decades, based principally on climate model simulations in which atmospheric CO_2 and trace gases increase steadily at rates estimated from observations. This is the first time that a global climate model has been used for simulating the climate effects of the transient growth of greenhouse gases, and as such it permits an estimate of when the greenhouse effect should begin to be evident above the level of natural climate variability. We emphasize that a number of caveats must be attached to the climate model results. But we also stress that the climate sensitivity of our model has been extensively compared to the sensitivity of other models and is consistent with available empirical evidence from past climate changes.

Our presentation is organized as a response to a letter from Chairman John Chafee of the United States Senate Subcommittee on Environmental Pollution of the Committee on Environment and Public Works who requested testimony at a hearing on the greenhouse effect on June 10, 1986. Specifically, his letter asked that the following topics be addressed:

- The nature of our work in modeling greenhouse climate effects
- How we test the models to determine their validity

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- The relative contribution of different greenhouse gases to possible future climate change

- The temperature changes predicted for the next few decades and the next century, assuming some reasonable growth in trace gases

- How the predicted temperatures compare to past temperatures experienced on the earth

- How temperature changes of the magnitude predicted might alter the number of days with temperatures above a given limit for Washington, D.C. and other U.S. cities

- Further evidence needed to confirm and quantify the greenhouse theory.

GLOBAL CLIMATE MODELING

In principle, global climate models are quite simple. For example, in our model (Hansen et al. 1983, hereafter referred to as paper 1) the earth is divided into 'gridboxes' as shown in Figure 1, and each gridbox is divided vertically into a number of layers, typically nine, in the atmosphere. Similarly, the ground or ocean in each gridbox is divided into several vertical layers. The mathematical equations describing the fundamental conservation laws of physics are solved numerically for each gridbox by a computer program, which calculates the transfer of mass, energy, and momentum from one box to another and also simulates physical processes within the boxes which represent sources and sinks of these substances.

Such global climate models, or GCMs, are able to reproduce the general features of the earth's climate. Climate variables such as temperature, winds, and storm tracks, and their variations from season to season, from latitude to latitude, and from continent to ocean, are represented realistically, at least in a qualitative sense. But the models are not sufficiently realistic to portray accurately regional patterns of precipitation, ocean currents, and other processes that are important for determining the practical consequences of climate trends because of greenhouse warming. Recent evidence that the large-scale ocean circulation may have undergone dramatic changes in the past (Broecker, Peteet, and Rind 1985) is of special concern; the representations of oceans in current GCMs are not sufficiently realistic to predict such phenomena.

Improvement of the climate models will depend especially upon better knowledge of physical processes occurring within the climate model gridboxes. These processes are represented by submodels or "parameterizations." For example, Figure 1b schematically illustrates convective clouds associated with convective transport of moisture, heat, and momentum between model layers. Although there have been major field experiments to study convection clouds, substantial work is needed to provide more realistic submodels for use in GCMs. Another example, one which is beginning to receive greater attention, concerns the role of vegetation and soil processes in the transfer of moisture, heat, and momentum between the earth's surface and the atmosphere. As a final example, we must have a better understanding of small-scale ocean

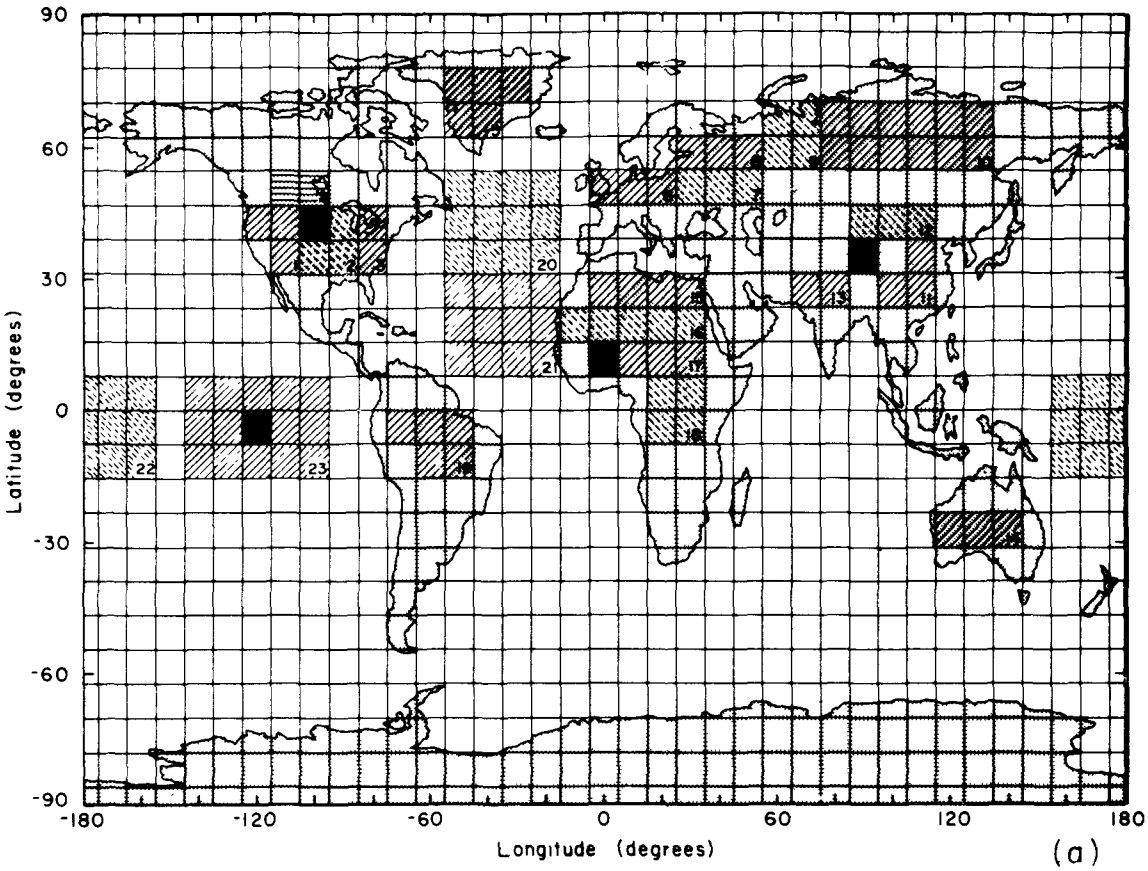


TABLE 1 Fundamental equations

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.

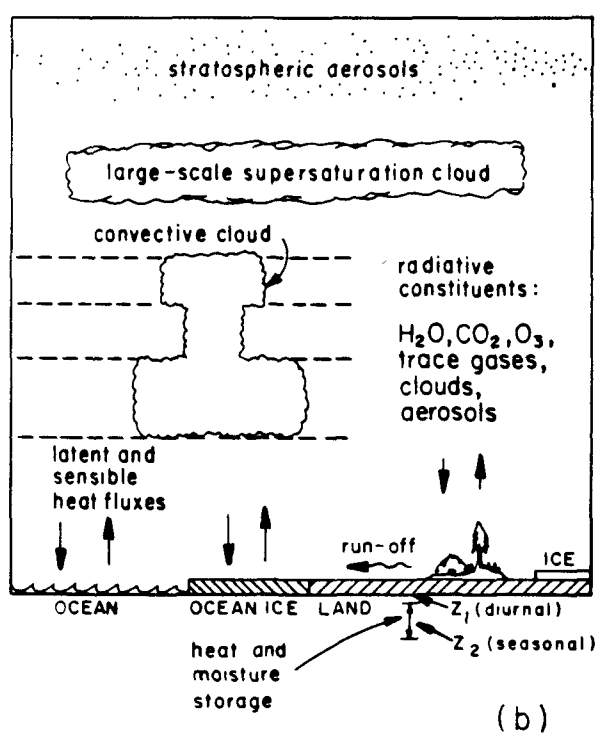


Figure 1.

mixing before we can develop an accurate model of global ocean circulation and currents.

A principal conclusion is that decades of research are likely to be required to improve climate models to the point that they can be used to predict local and regional climate changes with a high degree of confidence. Such improvements will be possible only if appropriate observations of the climate system and climate processes are carried out. In the meantime, climate models can provide a useful indication of the possible magnitude of future climate trends, although the results must be accompanied by appropriate explanations and caveats, especially the results at smaller scales.

Finally, we would like to stress one key characteristic of both climate model results and real-world climate, i.e., natural climate variability. Figure 2 illustrates the global mean temperature in a 100-year control run of our 3-D GCM. It can be seen that the temperature fluctuates, both from year to year and with decadal trends, even though the amount of atmospheric CO_2 and other climate "forcings" are unchanging in the model. Such variability or "noise" is a natural characteristic of the climate system. Although this phenomenon is captured by the governing fundamental equations in the climate model, individual fluctuations are not predictable. Thus, for any climate trend to be detected, it must exceed the level of natural climate variability.

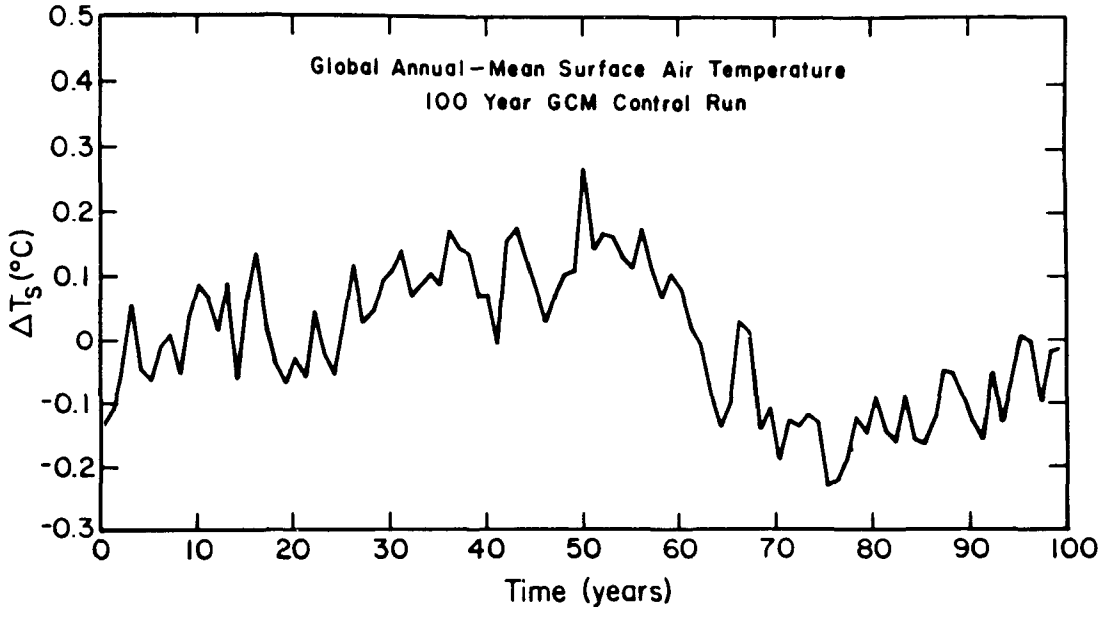


Figure. 2. Global-mean annual-mean surface air temperature in the 100-year control run with the GISS global climate model with predicted ocean temperature. Atmospheric CO_2, trace gases, and aerosols are unchanging during this run. The ocean-mixed layer has the observed seasonal and geographical depth variations and no exchange of heat with the deeper ocean.

TESTS OF CLIMATE MODELS

A good overall test of the greenhouse effect is provided by examining the climates of several planets--Mars, Earth, and Venus--which have a wide range of abundances of atmospheric greenhouse gases. These planets are warmer than they would be if they were simply in blackbody equilibrium with the energy absorbed from the sun. The observed greenhouse warmings are a few degrees on Mars, about 35 degrees on Earth, and several hundred degrees on Venus. The magnitude of these warmings is in excellent agreement with the greenhouse theory and simple climate models.

Another test, of more direct relevance, is provided by prehistoric climate variations on Earth. This test is only recently beginning to be exploited. The climate of the Earth has fluctuated between ice ages and interglacial warm periods several times during the past few hundred thousand years. It has been realized for more than a decade that small variations in the earth's orbital characteristics about the sun were the 'pacemakers' of the 10,000- to 100,000-year climate changes (Hays et al. 1976), but the mechanisms by which global temperature changes were produced remain uncertain. Recently it has been discovered that the atmospheric CO_2 abundance fluctuated along with ancient climate, and was thus a probable agent producing the global temperature changes. This inference of past CO_2 warming allows an empirical evaluation of climate sensitivity to a CO_2 change.

In particular, the paleoclimate record indicates that a CO_2 change of 50-100 parts per million (ppm) (Oeschger et al. 1984) is associated with a global mean temperature change of 4°-5°C (CLIMAP Project 1981). The global radiative forcing (ΔT_o) due to this CO_2 change, i.e., the surface temperature change which would occur if there were no climate "feedback" processes, can be accurately computed and is

$$\Delta T_o \sim 0.5^oC. \qquad (1)$$

Thus, under the assumption that the CO_2 change is the dominant forcing for the global temperature change, the total climate feedback factor f, defined by

$$\Delta T = f\Delta T_o, \qquad (2)$$

is $f \sim 10$ for the recent glacial-to-interglacial climate changes. Physical processes contributing to f have been analyzed (Hansen et al. 1984, hereafter referred to as paper 2) and it has been shown that a substantial part of the total feedback factor is due to the growth and decay of large continental ice sheets, a process which is not significant on the time scale of the next few decades. The feedback factor inferred from the paleoclimate data for processes that are relevant to a climate change on decadal time scales is $f \sim 2\text{-}4$.

The paleoclimate evidence thus indicates that if atmospheric CO_2 were doubled from, say, 300 ppm to 600 ppm, and the climate system were allowed to come to a new equilibrium, the earth would warm by

$$\Delta T(2*CO_2) \sim (2^o\text{-}4^oC) * \Delta T_o \sim 2.5^o\text{-}5^oC, \qquad (3)$$

where $\Delta T_0 \sim 1.25$ is the no-feedback radiative forcing due to doubling atmospheric CO_2.

The climate sensitivity inferred from paleoclimate evidence is reasonably consistent with the climate sensitivity estimated by several National Academy of Science studies (Charney et al. 1979; Smagorinsky et al. 1982),

$$\Delta T(2*CO_2) = 3^0 \pm 1.5^0C, \qquad (4)$$

which was based mainly on intercomparison and analysis of several different climate model studies. Thus there is general agreement about the magnitude of global climate sensitivity, but the uncertainty in its value is at least a factor of two.

Despite all the above evidence, the one truly convincing test of the models must be a comparison of the models' predictions with the observed response of the earth's climate to the present anthropogenically induced growth of atmospheric CO_2 and trace gases. Thus, we illustrate in Plate 2 the temperature changes that have occurred during the past century, a time during which CO_2 has increased from about 280 ppm to 340 ppm and several other trace gases have also increased.

The geographical patterns of temperature change (Plate 2a) contain a large amount of natural variability, as well as errors in regions where there are few stations and short records. The influence of the climate 'noise' and incomplete station coverage is reduced by averaging results over all longitudes. Plate 2b shows the resulting temperature trends for the period 1880-1984 as a function of latitude.

Several conclusions follow from the data illustrated in Plate 2. Most of the earth has warmed in the past 100 years, but there is a great amount of local variability. The global mean warming since 1880 is about 0.6°C (1°F), with both hemispheres warming by about that amount. Although the earth was about as warm in the 1930s and 1940s as it is in the 1980s, the earlier warming was more concentrated in the high latitudes of the Northern Hemisphere, while the recent warming is more global.

The global warming of 0.6°C in the past century is of the magnitude expected as a result of increasing CO_2 and trace gases. It is difficult to make a more definitive statement than that, in part because the greenhouse forcing is time dependent (most of the growth coming in the past 25 years) and the climate system has a finite response time, probably several decades (paper 2 and Hansen et al. 1985), so that only a part of the eventual warming due to these added gases has occurred as yet. Also, a warming of 0.6°C is not particularly large compared to climate fluctuations that have occurred in the past millenium, as illustrated below.

We show below that the expected greenhouse climate signal is rising rapidly and should soon rise well above the level of natural variability. This would provide strong empirical verification of the greenhouse effect.

PREDICTED TEMPERATURE CHANGES

The estimated contributions of different greenhouse gases to climate forcing is illustrated in Figure 3 for different periods. The CO_2 contribution is known accurately, within about 10 percent. The contributions of chlorofluorocarbons CCl_3F (F_{11}) and CCl_2F_2 (F_{12}), compounds which are entirely man made, are also known accurately. The CH_4 greenhouse contribution is less certain; there is some recent evidence suggesting that the CH_4 growth rate we assumed (0.6 percent per year in the 1960s, 1 percent per year in the 1970s, and 1.5 percent year in the 1980s) may be too high for the 1980s and perhaps too low for the 1960s (Rasmusson and Khalil 1986; Rinsland et al. 1985; Blake and Rowland 1986). The O_3 and stratospheric H_2O changes, based on a chemical model, are very uncertain and are best described as hypothetical; indeed, recent spotty observations of O_3 profiles do not support a positive greenhouse forcing due to changing O_3 (Lacis et al. 1986). Despite uncertainties about the trends of some of the gases, two firm conclusions can be made:

- In the past few decades the rate of increase of greenhouse forcing of the climate system has increased rapidly; it is now three to ten times greater than during the previous century, 1850-1960.

- Non-CO_2 greenhouse gases now add to the greenhouse effect at a rate comparable to that of CO_2.

We have carried out the first GCM simulations of climate trends due to the current changes of atmospheric CO_2 and trace gases. One disadvantage of presenting recent research results is that we cannot claim that the results have been confirmed by other climate modeling groups. However, the sensitivity of our global climate model has been compared and found to be similar to that of other climate models at the NSF National Center for Atmospheric Research (Washington and Meehl 1984) and the NOAA Geophysical Fluid Dynamics Laboratory (Manabe and Broccoli 1985; Wetherald and Manabe 1986). Thus we expect that the general conclusions discussed below would not be changed if the models of these other laboratories were used, provided that similar basic assumptions were made, for example, with regard to trace gas growth rates and ocean heat uptake.

The global climate model employed for these simulations is our model II documented in paper 1, which has an equilibrium global mean sensitivity of 4.2°C for doubled CO_2 as documented in paper 2. For these transient experiments the ocean mixed layer depth is based on climatology, including geographical and seasonal variations. Heat capacity of the ocean beneath the mixed layer is included by treating a heat perturbation as a passive tracer which can diffuse into the deeper ocean; the diffusion coefficient varies geographically as a function of the climatological local stability beneath the mixed layer, according to the empirical relation given in paper 2. Horizontal ocean heat transports are fixed as described in paper 2.

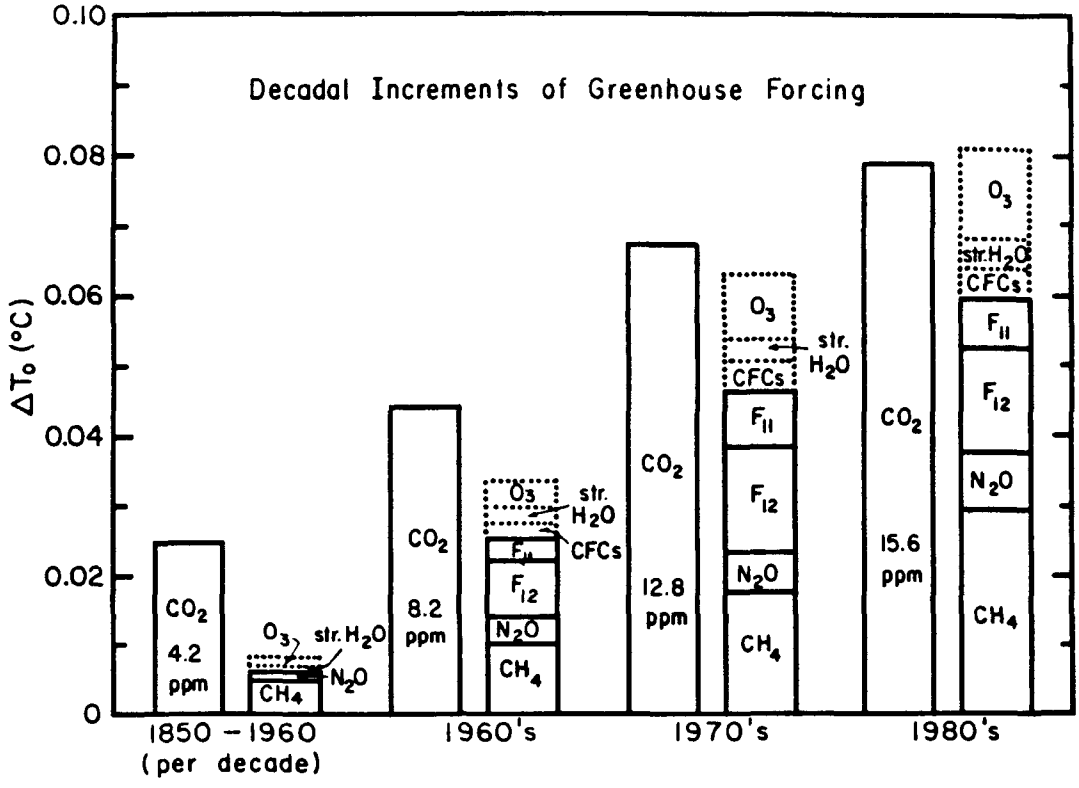


Figure 3. Decadal additions to global mean greenhouse forcing of the climate system. ΔT_0 is the computed temperature change at equilibrium for the estimated decadal increase in trace gas abundances, with no climate feedbacks included. Multiply ΔT_0 by the feedback factor f to get the equilibrium surface temperature change including feedback effects. Most of the estimated trace gas increases are based on measurements. However, the O_3 and stratospheric H_2O trends (dotted bars) are based principally on 1-D model calculations of Wuebbles et al. (1983).

Our GCM simulations begin in 1958, when CO_2 began to be monitored accurately by C.D. Keeling, and extend through the present into the future. We consider two scenarios, A and B, to allow for uncertainties about past trace gas changes and future CO_2 and trace gas changes. Scenario B includes only five greenhouse gases that have been measured reasonably well (CO_2, F_{11}, F_{12}, CH_4, N_2O) and it assumes that their growth rates will decrease rapidly during the next few decades. Scenario A includes an allowance to approximate the greenhouse forcing of the several other hypothesized gases in Figure 3, and it allows presently estimated growth rates to continue. We do not contend that Scenarios A and B represent extreme possibilities; however, they do help us to estimate how sensitive the conclusions are to assumptions about the climate forcings.

Scenario A achieves a radiative forcing equivalent to that for doubled CO_2 about 40 years from now, in the late 2020s. Scenario B achieves this level of forcing in about 2060. The more detailed trace gas scenario of Ramanathan et al. (1985) is close to Scenario A (see Figure 4). Finally, we note that both scenarios include some additional radiative forcing due to volcanic aerosols, a forcing that tends to cool the surface. The aerosol forcing is the same in the two scenarios for the period 1958-1986, with two significant coolings: 1963-66 (Mt. Agung) and 1982-85 (El Chichon). Scenario B assumes that the mean aerosol forcing in the future will be similar to that in the period 1958-1966, a period of active volcanism, while Scenario A assumes a negligible future volcanic forcing, as was the case for the period 1910-1960.

Global maps of temperature changes obtained in the GCM climate experiments are shown in Plate 3. The detailed geographical patterns of these changes are not to be taken seriously in view of the limitations of current GCMs mentioned above and the gross assumption about ocean heat transports. However, some of the large-scale features are more likely to be meaningful.

The warming in Scenario A at most midlatitude Northern Hemisphere land areas such as the United States is typically 0.5°-1.0°C (1°-2°F) by the decade 1990-2000 (Plate 3a) and 1°-2°C (2°-4°F) by the decade 2010-2020 (Plate 3b). Even in the latter decade the warming is much less than the equilibrium response to doubled CO_2 (Plate 3c) which has a warming of about 5°C in the United States. At all future times the largest temperature changes are in regions of sea ice and the smallest are at low and middle latitude ocean areas.

The global mean temperatures computed by the model are compared to observations in Figure 5 for the period 1958 to the present. In this period the greenhouse forcing of Scenarios A and B differ only by about 10 percent. It is apparent that the observed temperatures and the model results are consistent during this period. But the natural variability of temperature in both the real world and the model are sufficiently large that we can neither confirm nor refute the modeled greenhouse effect on the basis of current temperature trends.

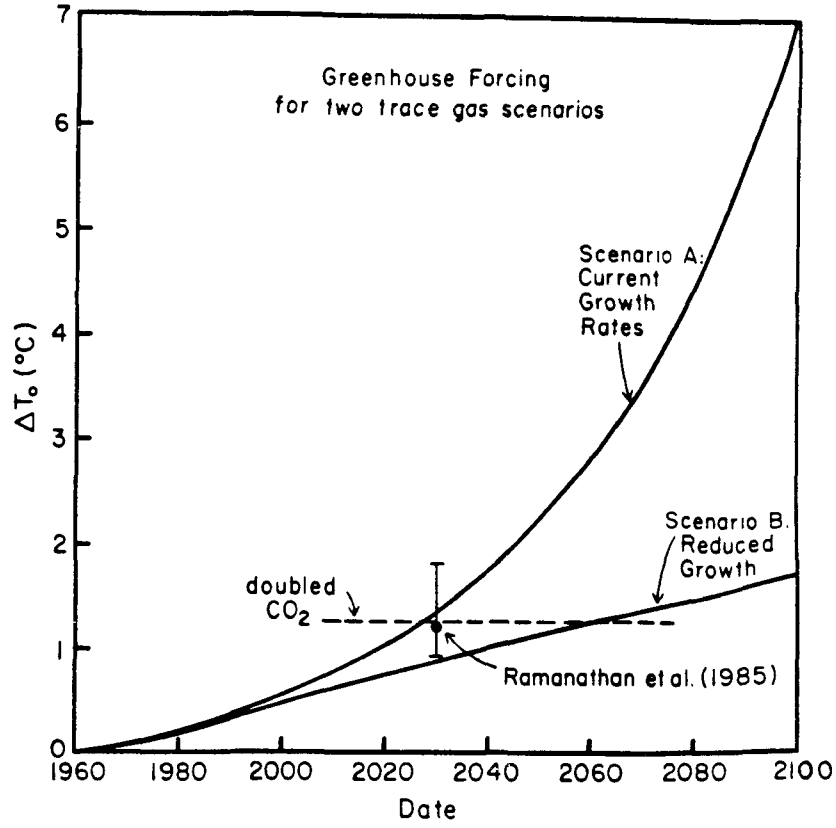


Figure 4. Greenhouse forcing for two trace gas scenarios. ΔT_o is the equilibrium warming with no climate feedbacks. Scenario B includes only CO_2, CH_4, N_2O, F_{12}, and F_{11}, and it assumes that their growth rates will decrease rapidly in the next 25 years. Scenario A includes an allowance for other trace gasses hypothesized in Figure 3 and it allows current growth rates to continue indefinitely.

In Scenario A CO_2 increases as observed by Keeling for the interval 1958-1984 and subsequently with a 1.5 percent growth of the annual increment. CCl_3F and CCl_2F_2 emissions are from reported rates to date and assume 3 percent per year^{-1} increased emission in the future, with atmospheric lifetimes for the gases of 75 and 150 years, respectively. CH_4 increases from 1.4 parts per billion in 1958 at a rate of 0.6 percent per year^{-1} until 1970, 1 percent per year^{-1} in the 1970s and 1.5 percent per year^{-1} thereafter. N_2O increases according to the semi-empirical formula of Weiss (1981), the rate being 0.1 percent per year^{-1} in 1958, 0.2 percent per year^{-1} in 1980, 0.4 percent per year^{-1} in 2000 and 0.9 percent per year^{-1} in 2030. Potential effects of several other trace gases (such as O_3, stratospheric H_2O, and chlorine and fluorine compounds other than F_{11} and F_{12}) are approximated by multiplying the CFC amount by the factor 2.

In Scenario B the growth of the annual increment in CO_2 is reduced from 1.5 percent today to 1 percent in 1990, 0.5 percent in 2000 and zero in 2010. The growth in annual emissions of CCl_3F and CCl_2F_2 is reduced from 3 percent today to 2 percent in 1990, 1 percent in 2000 and 0.5 percent in 2000. N_2O increases are based on Weiss' (1981) formula, but the parameter specifying annual growth in anthropogenic emissions decreases from 3.5 percent today to 2.5 percent in 1990, 1.5 percent in 2000 and 0.5 percent in 2010. No increases are included for other chlorofluorocarbons, ozone, stratospheric water or any other gases.

On the other hand, it is also apparent from Figure 5 that the predicted greenhouse warming for Scenario A rises above the level of natural variability by the 1990s. The standard deviation of the five year smoothed global temperature during the past century is $\sigma \sim 0.2^{o}C$. Thus a global warming of 0.6°C, compared to, say, the 1958-1980 mean temperature, would be a 3σ effect, significant at the 99 percent confidence level. The model predicts that such a warming will be achieved in the 1990s.

Indeed, the model predicts a temperature level in the next 15 years that has not existed on earth in the past 100,000 years, as illustrated below. In view of the significance of such conclusions, we stress here the principal caveats which must accompany the result:

- The model sensitivity is 4.2°C for doubled CO_2. Emergence of the warming signal above the level of natural climate variability will be delayed if the true sensitivity is less than that.

- The projection is based on Scenario A. If Scenario B is more realistic, emergence of the warming signal will be delayed. We estimate that Scenario B would delay the emergence of the signal by several years, but a more quantitative statement requires extension of the Scenario B simulation.

- Other major climate forcings that tend to counteract the greenhouse warming may occur during the next several years. As one example, satellite measurements indicate that solar irradiance decreased in the period 1980-1984 (cf. references in Kerr 1986) at a rate that would approximately cancel the increase in greenhouse forcing during the same period. Although decreases in solar irradiance are probably cyclical and must be balanced by comparable increases over a time scale of several decades, it is possible that a decreasing trend could continue for several more years. As a second example, an unusual increase in volcanic activity could conceivably counteract the greenhouse warming for as long as a decade or so: Scenario B contains a substantial amount of volcanic aerosols, similar to the amount in the volcanically active period 1958-1985, but it is possible to have a still greater level of volcanic activity.

- There may be crucial climate mechanisms that are omitted or poorly simulated in current climate models. An example is changes in ocean circulation, such as the formation of deep water (Bennett et al. 1985). If the rate of deep water formation is reduced, it is even possible that the North Atlantic and Europe may cool while most of the world is warming. A change in ocean circulation would also raise the possibility of a more rapid transition to a warmer climate, if it reduced the effective thermal inertia of the ocean and thus reduced the climate response time (paper 2; Hansen et al. 1985).

COMPARISON WITH PAST TEMPERATURES

Global temperature changes are illustrated in Figure 6 for the past century, millenium, and 25,000 years and in Figure 7 for the past 150,000 years. The global mean temperature has varied by about 0.5°C in the past century and 5°C in the past several hundred thousand years (National Academy

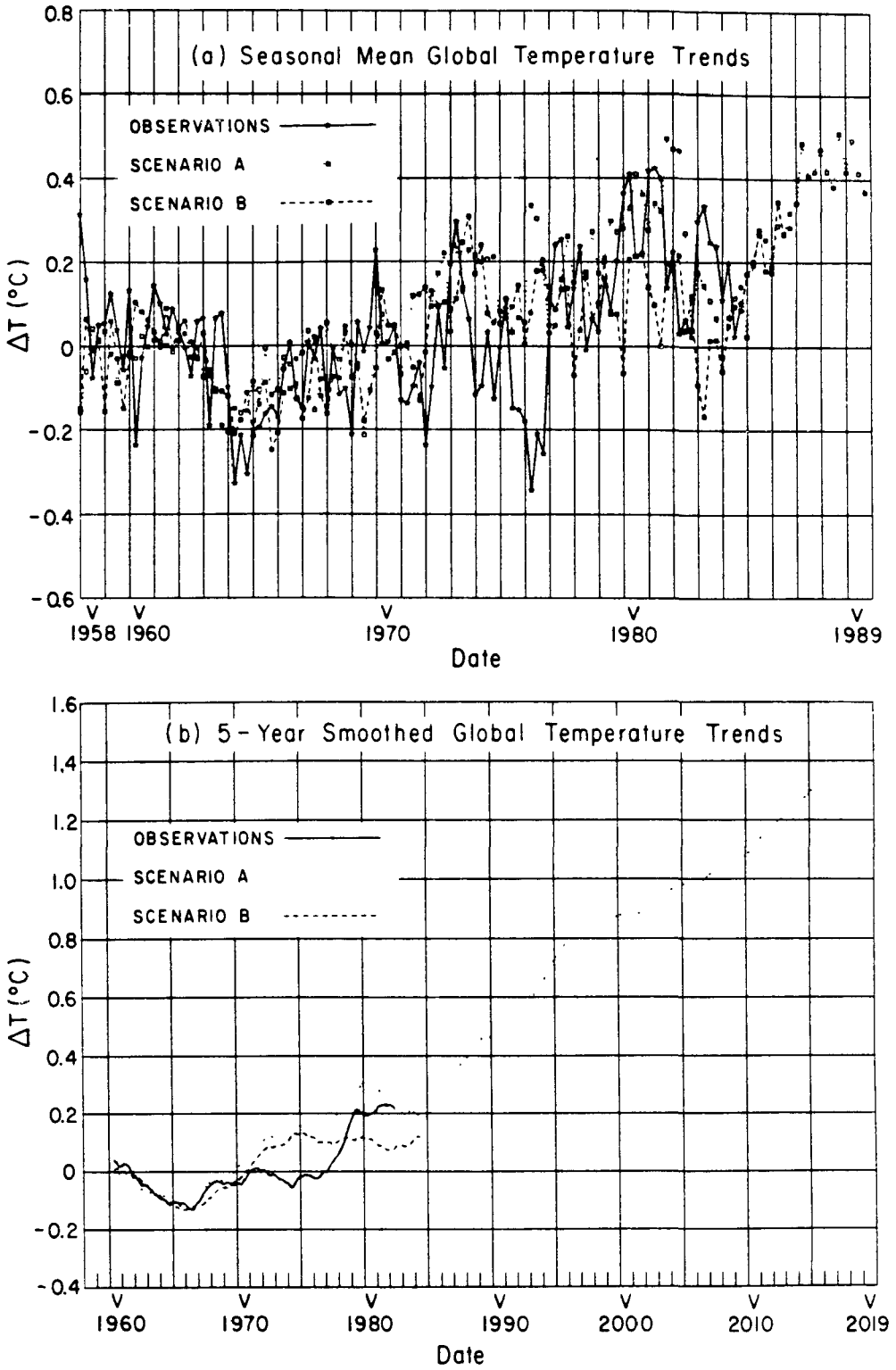


Figure 5. Global temperature trends from observations (solid line) and from calculations with the GISS global climate model. Part (a) shows the temperature anomalies plotted each season (December-January-February, March-April-May, etc.). Part (b) shows the 5-year smoothed results. Simulations have only been carried out into the future for Scenario A.

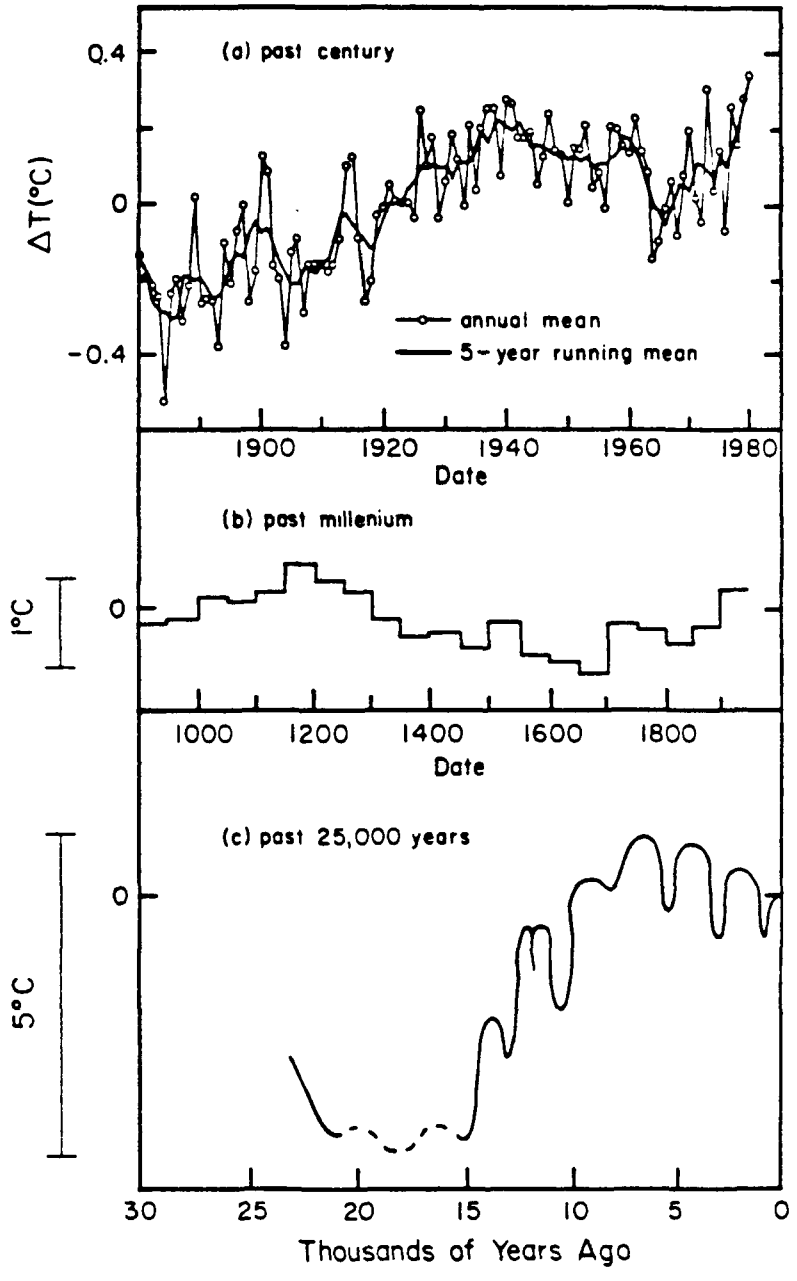


Figure 6. Global temperature trend for the past century (a), millenium (b), and 25,000 years (c). (a) is based on Hansen et al. 1981, updated through 1981. (b) is based on temperatures in central England, the tree limit in the White Mountains of California, and oxygen isotope measurements in the Greenland ice (W. Dansgaard, private communication), with the temperature scale set by the variations in the last 100 years. (c) is based on changes in tree lines, fluctuations of alpine and continental glaciers and shifts in vegetation patterns recorded in pollen spectra (National Academy of Sciences 1975), with the temperature scale set by the 3°-4°C cooling obtained in a 3-D climate model (Hansen et al. 1984) with the boundary conditions for 18,000 years ago. Thus the shapes of curves (b) and (c) are based on only Northern Hemisphere data.

of Sciences 1975). During the peak of the current interglacial (Altithermal period 5,000 to 10,000 years ago) the mean temperature is estimated to have been 0.5°-1.0°C warmer than today (Figure 6).

A comparison of the temperature changes projected for the next few decades with estimated temperatures for the past 150,000 years is shown in Figure 7. By the early twenty-first century the global temperature should have risen well above any level experienced in the past 100,000 years.

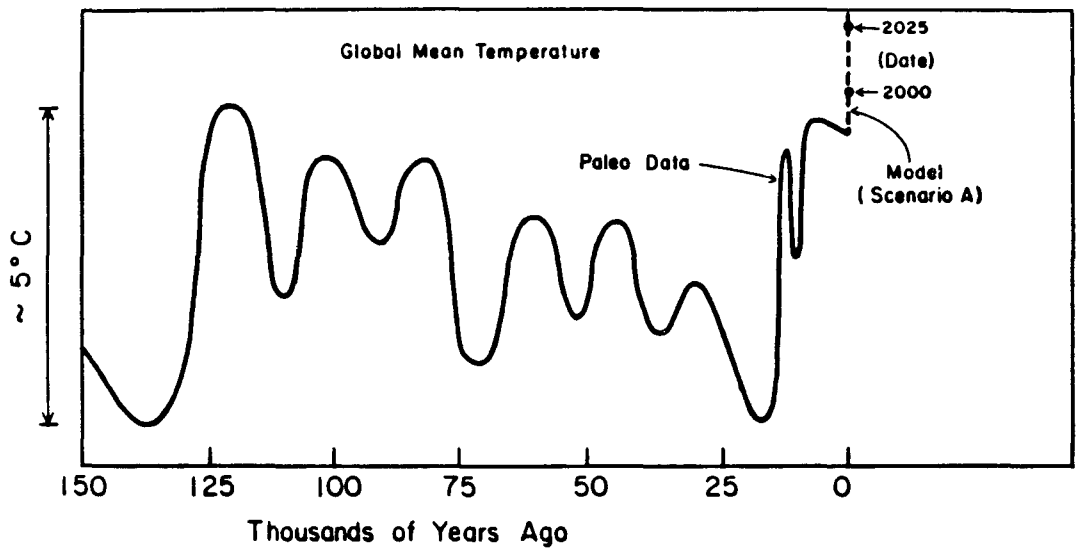


Figure 7. Global temperature trend for the past 150,000 years and as projected for the next few decades on the basis of the global climate model simulation with Scenario A trace gas trends.

TEMPERATURE CHANGES IN THE UNITED STATES

How might temperature changes of the magnitude predicted alter the number of days with temperatures above a given limit for Washington, D.C. and other U.S. cities? We estimate this by compiling climatological data for 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 gridbox that includes that city. This procedure tends to minimize the effects of any errors in the model's control run climatology. Although we should, in principle, also examine the effect of changes in higher moments of the temperature distribution, Mearns et al. (1984) have shown that changes in the higher moments have relatively little effect on the total number of days above a temperature extreme.

We have carried out this procedure for several U.S. cities for the equilibrium change in climate for doubled CO_2. Because of the climate system's finite response time, the results may be most applicable to some time in the middle of the twenty-first century, if the trace gas growth rate of Scenario A is approximately correct.

The results of this exercise for several cities in the United States are shown in Figure 8. The number of days per year in which the maximum daily temperature exceeds 38°C (100°F) increases from about one to twelve in Washington and from three to twenty in Omaha. The number of days with maximum temperature exceeding 32°C (90°F) increases from about thirty-five days to eighty-five days in both cities. The number of days per year in which the nighttime temperature does not fall below 27°C (80°F) increases from less than one day in both cities to nine days in Omaha and nineteen in Washington, D.C. Analogous results for six other U.S. cities are included in Figure 8.

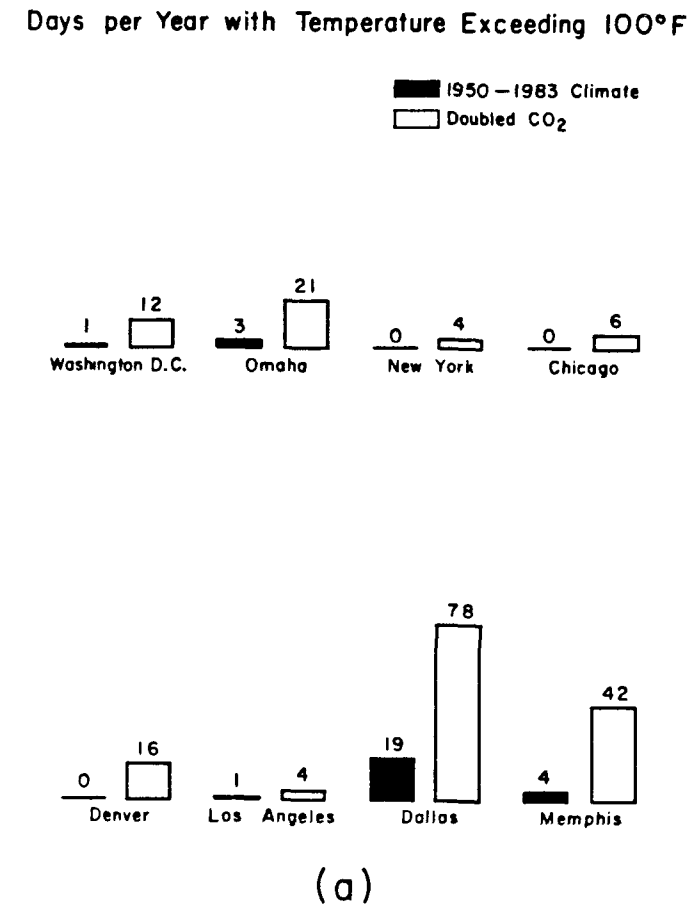
There are a number of reasons why these estimates may differ from the real world response. Principal among these are the following. First, the estimates are based on a model with a sensitivity of 4°C for doubled CO_2; the real world sensitivity is uncertain by about a factor of two. Second, the model assumes that the ocean will continue to operate 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.

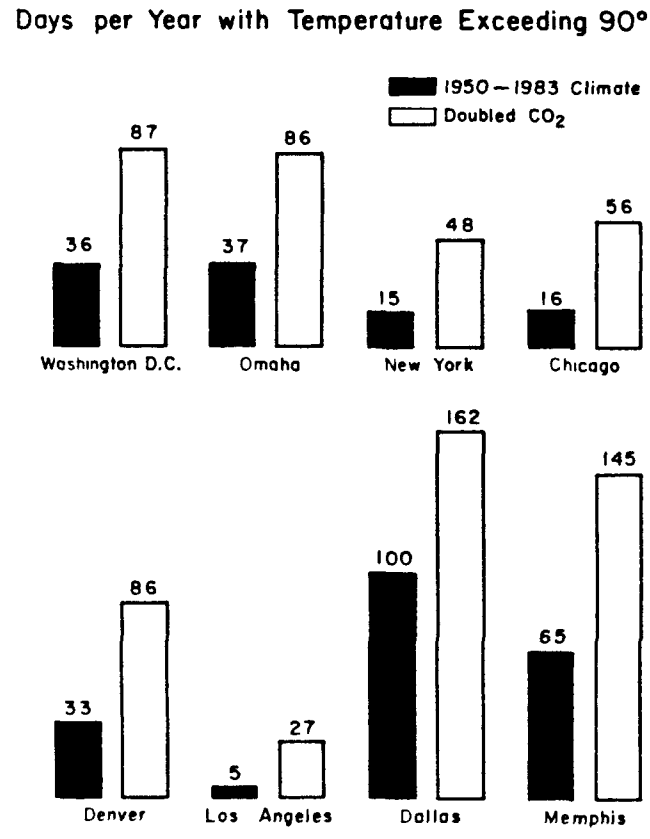
A number of expected effects of the greenhouse warming in the United States are summarized in Table 1. The summer cooling requirements in some United States cities will increase several times. On the other hand, heating degree days in the winter decrease on the order of 50 percent. The winter warming, expected to exceed that in summer, may also affect such things as the ability of indigenous forests to survive (Shantz and Hoffman 1986), and the amount, type, and distribution of precipitation. Table 1 also indicates that the growing season will increase in the United States, typically by fifty days, and it is expected that increasing atmospheric CO_2 will enhance plant growth (Lemon 1983). Nevertheless, the high midsummer temperatures could conceivably result in lower agricultural productivity, as occurred in (regional) midsummer heat waves in the United States in 1980 and 1986. Quantitative evaluation of beneficial and detrimental effects will require greatly improved climate forecast capabilities as well as research in societal impact.

We conclude that the magnitude of temperature changes predicted by current climate models is sufficiently great that, on the average, the warming will be very noticeable to the populations at middle latitudes. Other discussions of the practical impacts of greenhouse warming have focused on possible indirect effects such as changes of sea level, storm frequency, and drought. We believe, however, that the temperature changes themselves will substantially modify the environment and have a major impact on the quality of life in some regions.

EVIDENCE NEEDED TO CONFIRM AND QUANTIFY THE GREENHOUSE THEORY

From a scientific point of view, evidence confirming the essence of the greenhouse theory is already overwhelming. However, the greenhouse issue is not likely to receive the full attention it deserves until the global temperature rises above the level of natural climate variability. This will not occur at some sharp point in time, but rather gradually over a period of time. If our model is approximately correct, that time may be soon, within the next decade.





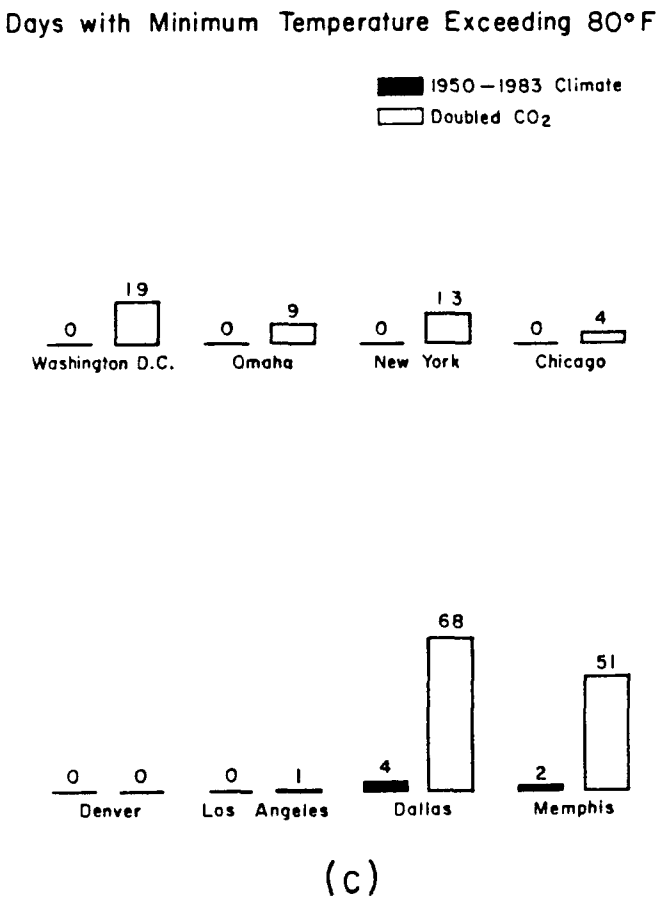


Figure 8. Annual number of days in several U.S. cities with (a) maximum temperature greater than 100°F, (b) maximum temperature greater than 90°F, and (c) minimum temperature greater than 80°F. The results for doubled CO_2 were generated by adding the warming in a doubled CO_2 climate model experiment to recorded temperatures for 1950-1983.

Table 1.

Table 1. Temperature increases, ΔT, due to doubled CO_2 for representative months; number of days per year in which the daily maximum temperature exceeded 100°F and 90°F, and in which the minimum temperature exceeded 80°F for the 1950-1983 and doubled CO_2 climates; number of cooling degree days (base 80°F), heating degree days (base 65°F) and length of growing season for the 1950-1983 climate and as estimated for doubled CO_2.

City	ΔT (°F)				Days T_{max}>100°F		Days T_{max}>90°F		Days T_{min}>80°F		Cooling Degree-Days		Heating Degree-Days		Growing Season (days)	
	Jan	Apr	July	Oct	Today	2*CO_2	Today	2*CO_2	Today	2*CO_2	Today	2*CO_2	Today	2*CO_2	Today	2*CO_2
Washington	7.9	7.2	6.6	7.1	1	12	36	87	0	19	92	470	4181	2642	233	278
New York	7.9	7.3	6.7	6.3	0	4	15	48	0	13	47	284	4948	3289	236	271
Chicago*	10.0	8.9	5.2	7.6	0	6	16	56	0	4	22	197	6636	4350	178	232
Omaha	10.4	9.0	6.2	8.4	3	21	37	86	0	9	81	396	6284	4041	179	231
Denver	11.7	8.7	6.1	9.9	0	16	33	86	0	0	4	118	6007	3659	162	206
Los Angeles	9.3	9.5	7.5	9.2	1	4	5	27	0	1	8	100	1442	212	365	365
Dallas	7.8	8.4	7.4	8.7	19	78	100	162	4	68	477	1343	2477	1205	253	313
Memphis	8.5	10.0	6.7	8.7	4	42	65	145	2	51	221	991	3249	1531	234	311

* Chicago's record based on 25 years 1959-1983.

When that point in time is reached people will begin to ask practical questions and want quantitative answers. We are now totally unprepared to provide information of the specificity that will be required. Our understanding of the climate system and our ability to model climate must be vastly improved. Some of the tasks, such as the development of a realistic ocean model appropriately interactive with atmospheric climate changes, 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. 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. Prestigious scientific groups, such as the Earth System Sciences Committee appointed by the NASA Advisory Council, have defined the required observations in detail.

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The Causes and Effects of Sea Level Rise

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INTRODUCTION

For the last several thousand years, sea level has risen so slowly that for most practical purposes it has been constant. As a result, people and other maritime species have had the opportunity to extensively develop the shorelines of the world. Whether one is talking about a vacation spot in Rio de Janeiro, swamps in Bangladesh, farmland in the Nile Delta, marshes along the Chesapeake Bay, or the merchants of Venice, life along the coast is in a sensitive balance with the level of the sea.

This balance would be upset by the rise in sea level that could result from the global warming projected by Hansen et al. (this volume). Such a warming could raise sea level one meter or more in the next century by expanding ocean water, melting mountain glaciers, and perhaps eventually causing polar ice sheets to melt or slide into the oceans. Sea level rise would inundate low-lying areas, drown coastal marshes and swamps, erode beaches, exacerbate flooding, and increase the salinity of rivers, bays, and aquifers throughout the world.

This paper provides an overview of the causes and effects of sea level rise.

CAUSES OF SEA LEVEL RISE

Past Trends in Sea Level

The worldwide average sea level depends primarily on (a) the shape and size of ocean basins, (b) the amount of water in the oceans, and (c) the average density of seawater. Subsidence, emergence, and other local factors can cause trends in "relative sea level" at particular locations to differ from trends in "global sea level."

Hays and Pitman (1973) analyzed fossil records and concluded that over the last 100 million years, changes in mid-ocean ridge systems have caused sea level to rise and fall over 300 meters. However, Clark, Farrell, and Peltier (1978) have pointed out that these changes have accounted for sea level changes of less than one millimeter per century. No published study has indicated that this determinant of sea level is likely to have a significant impact in the next century.

The impact of climate on sea level has been more pronounced. 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 (Don, Farrand, and Ewing 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). Table 1 shows estimates by Hollin and Barry (1979) and Flint (1971) 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 60 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 period, which was one to two degrees warmer (Moore 1982; Mercer 1968). Because the West Antarctic Ice Sheet is marine-based and thought to be vulnerable to climatic warming, attention has focused on this source for the higher sea level. Mercer (1968) found that lake sediments and other evidence suggested that summer temperatures in Antarctica have been 7° to 10°C higher than today at some point in the last two million years, probably during the last interglacial period 125,000 years ago, and that such temperatures could have caused a disintegration of the West Antarctic Ice Sheet.

Tidal gauges have been available to measure the change in sea level at particular locations over the last century. Studies combining these measurements to estimate global trends have concluded that sea level has risen 1.0 to 1.5 mm/yr during the last century (Barnett 1983; Gornitz, Lebedeff, and Hansen 1982; Fairbridge and Krebs 1962). Barnett (1983) found the rate of sea level rise for the last fifty years to be between 2.0 and 2.5 mm/yr, while in the previous fifty years there was little change; however, the acceleration of the rate of sea level rise was not statistically significant. Emery and Aubrey (1985, n.d.) have filtered out estimated land surface movements in their analyses of tidal gauge records in northern Europe and western North America, and have found an acceleration in the of sea level rise over the last century.[1] Braatz and Aubrey (n.d.) have found that the rate of

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[1] This result was reported in the North America study. The data also shows it to be true in the northern Europe study, but the result was not reported. David Aubrey, Woods Hole Oceanographic institute, Woods Hole, Massachusetts, personal communication.

Table 1. Snow and Ice Components (Modified from Hollin and Barry 1979)

	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Sea-Level Equivalent[a] (m)
Land ice: East Antarctica[b]	9.86	25.92	64.8
West Antarctica[c]	2.34	3.40	8.5
Greenland	1.7	3.0	7.6
Small ice caps and mountain glaciers (Hollin and Barry 1979; Flint 1971)	0.54	0.12	0.3 0.6
Permafrost (excluding Antarctica):			0.6
Continuous	7.6	0.03 to	0.08 to
Discontinuous	17.3	0.7	0.17
Sea ice: Arctic[d]			
Late February	14.0	0.05	
Late August	7.0	0.02	
Antarctic[e]			
September	18.4	0.06	
February	3.6	0.01	
Land Snow Cover[f]			
N. Hemisphere			
Early February	46.3	0.002	
Late August	3.7		
S. Hemisphere			
Late July	0.85		
Early May	0.07		

[a] 400,000 km^3 of ice is equivalent to 1 m global sea level.
[b] Grounded ice sheet, excluding peripheral, floating ice shelves (which do not affect sea level). The shelves have a total area of 1.62 x 10^6 km^2 and a volume of 0.79 x 10^6 km^3 (Drewry and Heim 1983).
[c] Including the Antarctic Peninsula.
[d] Excluding the Sea of Okhotsk, the Baltic Sea, and the Gulf of St. Lawrence (Walsh and Johnson 1979). Maximum ice extents in these areas are 0.7 million, 0.4 million, and 0.2 million km^2, respectively.
[e] Actual ice area excluding open water (Zwally et al. 1983). Ice extent ranges between 4 million and 20 million km^2.
[f] Snow cover includes that on land ice but excludes snow-covered sea ice (Dewey and Heim 1981).

Source: Glaciers, Ice Sheets, and Sea Level, National Academy Press, p. 272.

relative sea level rise on the east coasts of North America accelerated after 1934.

Several researchers have attempted to explain the source of current trends in sea level. Barnett (1984) and Gornitz, Lebedeff, and Hansen (1982) estimate that thermal expansion of the upper layers of the oceans resulting from the observed global warming of 0.4°C in the last century could be responsible for a rise of 0.4 to 0.5 millimeter per year. Roemmich and Wunsch (1984) examined temperature and salinity measurements at Bermuda, found that the 4°C isotherm had migrated 100 meters downward, and concluded that the resulting expansion of ocean water could be responsible for some or all of the observed rise in relative sea level. Roemmich (1985) showed that the warming trend 700 meters below the surface was statistically significant. However, Barnett (1983) found no significant trend based on an examination of the upper layers of the ocean. Nevertheless, Braatz and Aubrey (n.d.) note that long-term steric changes in the ocean are not confined to the upper layers of the oceans, which implies that the Barnett analysis does not necessarily contradict the Roemmich and Wunsch conclusion.

Meier (1984) estimates that retreat of alpine glaciers and small ice caps could be responsible for a current contribution to sea level of between 0.2 and 0.72 millimeters per year. The National Academy of Sciences (NAS) Polar Research Board (Meier 1985) concluded that existing information is insufficient to determine whether the impacts of Greenland and Antarctica are positive, negative, or zero. Although the estimated global warming of the last century appears at least partly responsible for the last century's rise in sea level, no study has demonstrated that global warming might be responsible for an accelerated 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 within 40 years.

Subsequent investigations have concluded that such a rapid rise is unlikely. Hughes (1983) estimated that such a disintegration would take at least two hundred years, and Bentley (1983), five hundred. Other researchers have estimated that this process could 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. The best understood factors are the thermal expansion of ocean water and the melting of alpine glaciers. In the National Academy of Sciences report Changing Climate, Revelle (1983) used the model of Cess and Goldenberg (1981) to estimate temperature increases at various depths and latitudes resulting from a 4.2°C warming by 2050-2060 (Figure 1). While noting that his assumed time constant of 33 years probably resulted in a conservatively low estimate, he estimated that temperature increases would result in an expansion of the upper ocean sufficient to raise sea level thirty centimeters.

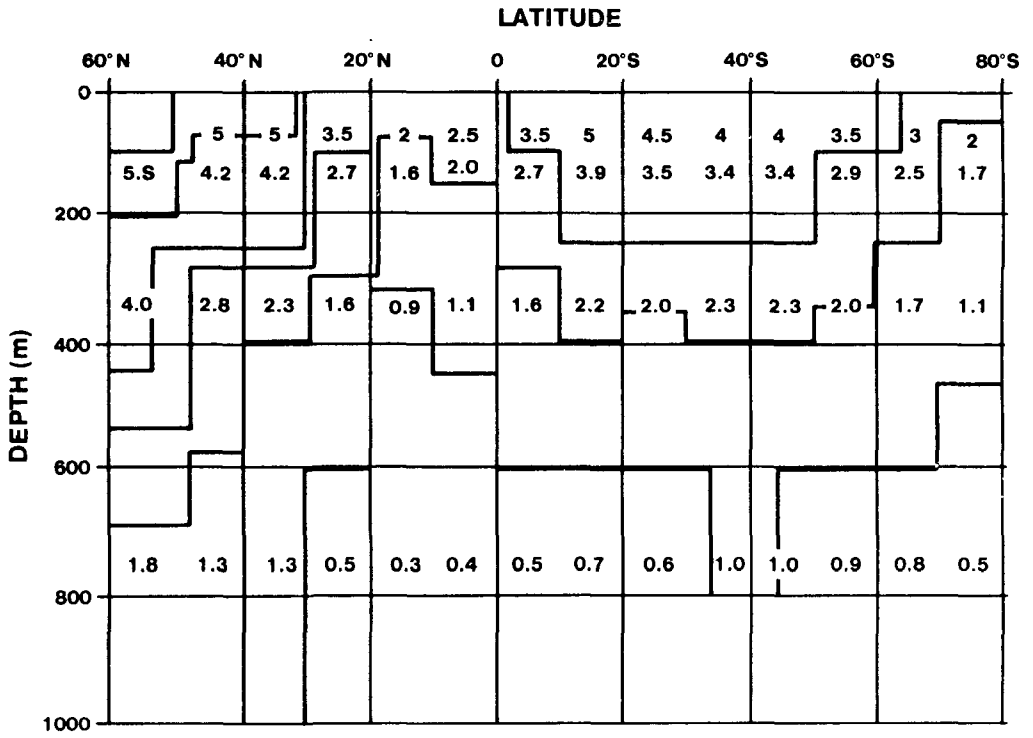

Figure 1. Computed near-equilibrium changes in ocean temperature for a doubling of atmospheric carbon dioxide and probable increase in other greenhouse gases, about 2080. The surface temperature increase is based on Flohn's (1982) prognosis.

Using a model of the oceans developed by Lacis et al. (1981), Hoffman, Wells, and Titus (1985) examined a variety of possible scenarios of future emissions of greenhouse gases and global warming. They estimated that a warming of between 1° and 2.6°C could result in a thermal expansion contribution to sea level of between 12 and 26 cm by 2050. They also estimated that a global warming of 2.3° to 7.0°C by 2100 would result in thermal expansion of 28-83 cm by that year.

Revelle (1983) suggested that while he could not estimate the future contribution of alpine glaciers to sea level rise, a contribution of 12 centimeters through 2080 would be reasonable. Meier (1984) used glacier balance and volume change data for twenty-five glaciers where the available record exceeded fifty years to estimate the relationship between historic temperature increases and the resulting negative mass balances of the glaciers. He estimated that a 28-mm rise had resulted from a warming of 0.5°C, and concluded that a 1.5° to 4.5°C warming would result in a rise of 8-25 cm in the next century. Using these results, the NAS Polar Board concluded that the contribution of glaciers and small ice caps through 2100 is likely to be 10 to 30 cm (Meier et al. 1985). They noted that the gradual depletion of remaining ice cover might reduce the contribution of sea level rise somewhat. However, the contribution might also be greater, given that the historic rise took place over a sixty-year period, while the forecast period is over one hundred years. Using Meier's estimated relationship between global warming and the alpine contribution, Hoffman, Wells, and Titus (1986) estimated alpine contributions through 2100 at 12-38 cm for a global warming of 2.3° to 7.0°C.

The first published estimate of the contribution of Greenland glacier meltwater to sea level was Revelle's (1983) estimate of 12 cm through the year 2080. Using estimates by Ambach (1980, 1982) that the equilibrium line (between snowfall accumulation and melting) rises one hundred meters for each 0.6°C rise in air temperatures, he concluded that the projected 6°C warming of Greenland would be likely to raise the equilibrium line 1,000 meters. He estimated that such a change in the equilibrium line would result in a 12-cm contribution to sea level rise for the next century.

The NAS Polar Board (Meier et al. 1985) noted that the large ablation area makes Greenland a "significant potential contributor of meltwater to the ocean if climatic warming causes an increase in the rate of ablation and an upward shift of the equilibrium line." They found that a 1,000-m rise in the equilibrium line would result in a contribution of 30 cm through 2100. However, because Ambach (1985) found the relationship between the equilibrium line and temperature to be 77 meters per degree (C), the panel concluded that a 500-m shift in the equilibrium line would be more likely. Based on the assumption of a 6.5°C warming by 2050 and constant temperatures thereafter, the panel estimated that such a change would contribute about 10 cm to sea level through 2100, but also noted that "for an extreme but highly unlikely case, with the equilibrium line raised 1,000 m, the total rise would be 26 centimeters." Although Bindschadler (1985), had treated the two cases as equally plausible, his analysis was conducted before the results of Ambach (1985) were known; he has since indicated agreement with the findings of Meier et al. (1985).[2]

Available estimates of the Greenland contribution assume that all meltwater flows into the oceans and that the ice dynamics of the glaciers do not change. The NAS Polar Board suggested that some of the water would refreeze, decreasing the contribution to sea level rise. Although a change in ice dynamics might imply additional deglaciation and increase the rate of sea level rise, the panel assumed that such changes were unlikely to occur in the next century.

The potential impact of a global warming on Antarctica in the next century is the least certain of all the factors by which a global warming might contribute to sea level rise. Meltwater from East Antarctica might make a significant contribution by the year 2100, but no one has estimated it.[3] The contribution of ice sliding into the oceans, known as "deglaciation," has been the subject of several studies.

Bentley (1983) examined the processes by which a deglaciation of Antarctica might occur. First an accelerated melting of the undersides of the Ross and Filchner-Ronne ice shelves would occur due to warmer water circulating underneath them. The thinning of these ice shelves could cause them to become unpinned and their grounding lines to retreat. Revelle (1983) suggests that the ice shelves might disappear in 100 years, after which time the Antarctic ice streams would flow directly into the oceans, without the back

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2 Robert Bindschadler, Goddard Space Flight Center, Greenbelt, Maryland, personal communication.

3 James Hansen, Goddard Institute for Space Studies, New York, personal communication to J.S. Hoffman.

pressure of the ice shelves. Bentley suggests that all the ice could be discharged over a period of 500 years.

Although a West Antarctic deglaciation would occur over a period of centuries, it is possible that an irreversible deglaciation could commence before 2050. If the ice shelves thinned more than about one meter per year, Thomas, Sanderson, and Rose (1979) suggested that the ice would move into the sea at a sufficient speed that even a cooling back to the temperatures of today would not be sufficient to result in a reformation of the ice shelf.

To estimate the likely Antarctic contribution for the next century, Thomas (1985) developed four scenarios measuring the impact of a 3°C global warming by 2050:

- A shelf melting rate of 1 m/yr with seaward ice fronts remaining at present locations--implies a rise of 28 cm by the year 2100.
- A shelf melting rate of 1 m/yr with ice fronts calving back to a line linking the areas where the shelf is grounded, during the 2050s--implies a rise of 1.6 m by 2100.
- Same as case 1 but with a melt rate of 3 m/yr--implies a rise of 1 m by 2100.
- Same as case 2 but with a melt rate of 3 m/yr--implies a rise of 2.2 m by 2100.

Thomas concluded that the 28-cm rise implied by case 1 would be most likely. He also stated that even if enhanced calving did occur, it would be likely to occur after 2050, "suggesting that probably associated sea level rise would be closer to the 1 m of case 3 than the 2.2 m of case 4."

The NAS Polar Board (Meier et al. 1985) evaluated the Thomas study and papers by Lingle (1985) and Fastook (1985). Although Lingle estimated that the contribution of West Antarctica through 2100 would be 3 to 5 cm, he did not evaluate the contribution from East Antarctica, while Fastook made no estimate for the year 2100. Thus, the panel concluded that "imposing reasonable limits" on Thomas' model yields a range of 20 to 80 cm by 2100 for the Antarctic contribution. However, they also noted several factors that could reduce the amount of ice discharged into the sea: the removal of the warmest ice from the ice shelves, the retreat of grounding lines, and increased lateral shear stress. They also concluded that increased precipitation over Antarctica <u>might</u> increase the size of the polar ice sheets there. Thus, the panel concluded that Antarctica could cause a rise in sea level up to 1 m, or a drop of 10 cm, with a rise between 0 and 30 cm most likely.

Table 2 summarizes the various estimates of global sea level rise. The report <u>Projecting Sea Level Rise</u> (Hoffman, Keyes, and Titus 1983) estimated that the rise would be between 56 and 345 cm, with a probable rise between 144 and 217 cm. Revelle (1983) estimated that the rise was likely to be 70 cm, ignoring the impact of a global warming on Antarctica; Revelle also noted that the latter contribution was likely to be 1 to 2 m per century after 2050, but declined to add that to his estimate. The NAS Polar Board (Meier et al. 1985)

Table 2. 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).

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 of Hoffman, Wells, and Titus (1985) were similar to the estimates of Hoffman Keyes, and Titus (1983) for the year 2100, but for the year 2025, they lowered their estimate from 26-39 cm to 10-21 cm.

Future Trends in Local Sea Level

Although most attention has focused on projections of global sea level, impacts on particular areas would depend on local relative sea level. Tidal gauge measurements suggest that relative sea level has risen 10 to 20 cm per century more rapidly than the worldwide average along much of the U.S. coast (Hicks, DeBaugh, and Hickman 1983). However, Louisiana is subsiding close to 1 m per century, while parts of Alaska are emerging 10 or more cm per century. Bruun argues that throughout most of the world, sea level has been rising. However, Bird (Volume 4) argues that sea level appears to be stable in Australia, which may imply that future rates of sea level rise will also be 10 to 15 cm per century less than the worldwide average.

Local subsidence and emergence are caused by a variety of factors. Rebound from the retreat of glaciers after the last ice age has resulted in the emergence of Alaska and parts of Scandinavia. The emergence in polar latitudes has resulted in subsidence in other areas. Groundwater pumping has caused rapid subsidence around Houston, Texas; Taipai, Taiwan; and Bangkok, Thailand, among other areas (Leatherman 1984; Kuo, Volume 4). River deltas and other newly created land subside as the unconsolidated materials compact.

Although subsidence and emergence trends may change in the future, particularly where anthropogenic causes are curtailed, no one has linked these causes to future climate change in the next century. However, the removal of ice from Greenland and Antarctica would deform the ocean floor. Clark and Lingle have (1977) calculated the impact of a uniform 1-m contribution from West Antarctica. They concluded that relative sea level at Hawaii would increase by an additional 25 cm, and that along much of the U.S. Atlantic and Gulf Coasts there would be an additional 15 cm. On the other hand, sea level would drop at Cape Horn by nearly 10 cm, and the rise along the southern half of the Argentine and Chilean coasts would be less than 75 cm.

Other influences on local sea level that might change as a result of a global warming include currents, winds, and freshwater flow into estuaries. None of these impacts, however, has been estimated.

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. Substantial research has been done on the implications of sea level rise for coastal erosion and wetlands, while relatively little work has been done in the other areas.

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, also described by Park, Armentano, and Cloohan in Volume 4. 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 1 m 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; Redfield 1972, 1967; Davis 1985). As sea level rose, new wetlands formed inland while the seaward boundary was maintained (Figure 2a, 2b). Because the wetland area has expanded, Titus, Henderson, and Teal (1984) hypothesized that one would expect a concave marsh profile, i.e., that there is more marsh area than the area found immediately above the marsh. Thus, if sea level rose more rapidly than the marsh's ability to keep pace, there would be a net loss of wetlands (Figure 2c). Moreover, a complete loss might occur if protection of developed areas prevented the inland formation of new wetlands (Figure 2d).

Kana, Baca, and Williams (1986) and Kana et al. (n.d.) surveyed marsh transects in the areas of Charleston, South Carolina, and two sites near Long Beach Island, New Jersey, to evaluate the concavity of wetland profiles and the vulnerability of wetlands to a rise in sea level. Their data from the Charleston area showed all the marsh to be between 30 and 110 cm above current sea level, an elevation range of 80 cm. The area with a similar elevation range just above the marsh was only 20 percent as large. Thus, a rise in sea level exceeding vertical marsh accretion by 80 cm would result in an 80 percent loss of wetlands. In the New Jersey sites, the marsh was also found within an elevation range of 80 cm; a rise in sea level 80 cm in excess of marsh accretion would result in 67 to 90 percent losses.

The future ability of marshes to accrete vertically is uncertain. Based on field studies by Ward and Domeracki (1978), Hatton et al. (1983), Meyerson (1972), and Stearns and MacCreary (1957), Kana et al. (n.d.) concluded that current vertical accretion rates are approximately 4 to 6 mm/yr in the two case study areas, greater than the current rate of sea level rise but less than the rates of rise projected for the next century. If current accretion trends continue, then 87 and 160 cm rises by 2075 would imply 50 and 80 percent losses of wetlands in the Charleston area. Kana et al. (n.d.) also estimated 80 percent losses in the New Jersey sites for a 160-cm rise through 2075. However, because the high marsh dominates in that area, they concluded that the principal impact of an 87-cm rise by 2075 would be the conversion of high marsh to low marsh.

In both cases, the losses of marsh could be greater if inland areas are developed and protected with bulkheads or levees. Because there is a buffer zone between developed areas and the marsh in South Carolina protecting development from a 160-cm rise would increase the loss from 80-90 percent. Without the buffer, the loss would be close to 100 percent.

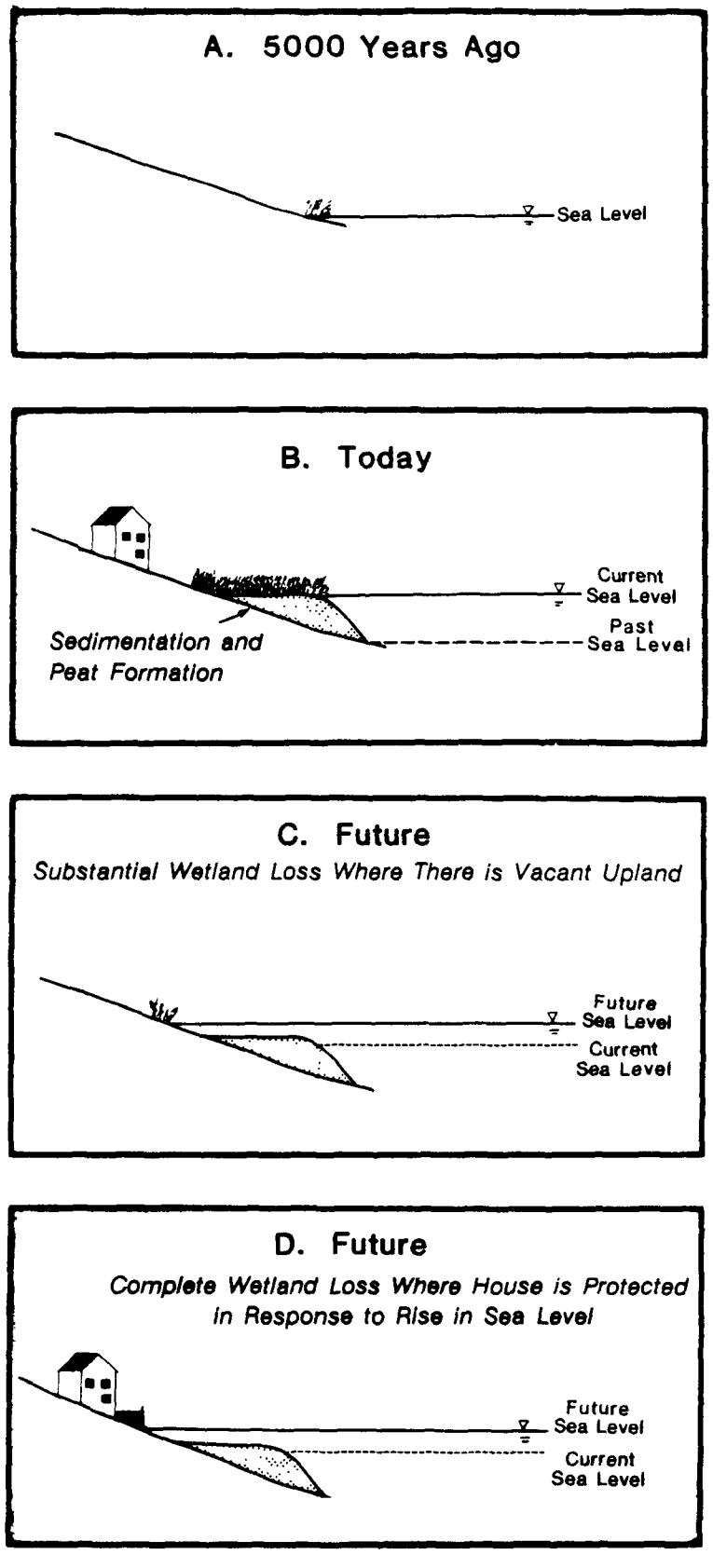

Figure 2. Evolution of Marsh as Sea Level Rises

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 majority of the Louisiana wetlands are 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 kept pace with this rate of relative sea level rise, because of the sediment the Mississippi River conveyed to the wetlands.

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, fresh water, and nutrients to the wetlands. As a result, over 100 square kilometers of wetlands convert to open water every year (Gagliano et al. 1983). A substantial rise in sea level would further accelerate the process of wetland loss in Louisiana.

To develop an understanding of the potential nationwide impact of sea level rise on coastal wetlands in the United States, Park, Armentano, and Cloonan (Volume 4) use topographic maps to characterize wetland elevations at fifty-two sites comprising 4800 square kilometers (1.2 million acres) of wetlands, over 17 percent of all U.S. coastal wetlands (see also Armentano, Park, and Cloonan n.d.). Using published vertical accretion rates, they estimate the impact of 1.4 and 2.1 m rises in sea level through the year 2100 for each of the sites. Park, Armentano, and Cloonan (Volume 4) estimate that these scenarios imply losses of 40 and 76 percent of the existing coastal wetlands in their sample, which could be reduced to 22 and 58 percent if new wetlands are allowed to form inland. However, Titus (n.d.) found that if the Park et al. sample is weighted according to an inventory of wetlands in particular areas (Alexander, Broutman, and Field 1986), the resulting estimates of U.S. wetland loss are somewhat higher, 47-82 percent of existing wetlands, with a potential for reducing those losses to 31 to 70 percent.

Throughout the world, people have dammed, leveed, and channelized major rivers, curtailing the amount of sediment that reaches river deltas. Even at today's rate of sea level rise, substantial amounts of land are converting to open water in Egypt and Mexico (Milliman and Meade 1983). Other deltas, such as the Ganges in Bangladesh and India, are currently expanding seaward. These areas would require increased sediment, however, to keep pace with an accelerated rise in sea level. Additional projects to divert the natural flow of river water would increase the vulnerability of these areas to a rise in sea level. Broadus et al. (Volume 4) examine this issue in detail for Egypt and Bangladesh.

Plate 4 (appearing immediately before this section) shows the projected land loss for Bangladesh for two scenarios:

- Low--a 50-cm global rise in sea level with current rates of subsidence and sedimentation

- High--a 200- to 250-cm rise with alterred sedimentation due to additional dams.

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 governments in Louisiana have proposed to artificially control 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 of lead time to permit the design of new mobile structures and the depreciation of the old immobile structures.

Inundation

Although coastal wetlands are found at the lowest elevations, inundation of lowland could also be important in some areas, particularly if sea level rises at least one meter. Unfortunately, the convention of ten-foot contours in the mapping of most coastal areas has prevented a general assessment of land loss. Although a few case studies have been conducted in the United States, very few studies have been undertaken to quantify the potential impacts on other countries, other than the paper by Broadus et al. (Volume 4).

Kana et al. (1984) used data from aerial photographs to assess elevations in the area around Charleston. They concluded that 160- and 230-cm rises would result in 30 and 46 percent losses of the area's dry land, respectively. Leatherman (1984) estimated that such rises would result in 9 and 12 percent losses of the land in the area of Galveston and Texas City, Texas, assuming that the elaborate network of seawalls and levees were maintained. (Many of the summary results from Leatherman 1984; Kana et al. 1984; and Gibbs 1984 appear in the appendix of Titus et al. 1984.)

Schneider and Chen (1980) conducted the first nationwide assessment of the inundation from projected sea level rise. Unfortunately, the smallest rise in sea level they considered was a 4.5-m (15-ft) rise, in part because smaller contours are not generally available in topographic maps. Nevertheless, their findings suggest which coastal states would be most vulnerable: Louisiana (which would lose 28 percent of its land and 51 percent of its wealth), Florida (24 and 52 percent), Delaware (16 and 18 percent), Washington, D.C. (15 and 15 percent), Maryland (12 and 5 percent), and New Jersey (10 and 9 percent).

As with wetland loss, the responses to inundation fall broadly into the categories of retreat and holding back the sea. Levees are used extensively in the Netherlands and New Orleans to prevent the flooding of areas below sea level and could be similarly constructed around other major cities. In sparsely developed areas, however, the cost of a levee might be greater than the value of the property being protected. Moreover, even where levees prove to be cost-effective, the environmental implications of replacing natural shorelines with manmade structures would need to be considered.

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 extending from the dunes out to the point where the water is too deep for waves to have a significant impact on the bottom (generally a depth of about 10 meters). By comparison, inundation depends only on the slope immediately above the original sea level. Because beach profiles are generally flatter than 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. (See Figure 3.)

As Bird (Volume 4) emphasizes, processes other than sea level rise also contribute to erosion, including storms, structures, currents, and alongshore transport. Because sea level has risen slowly in recent centuries, verification of the Bruun Rule on the open coast has been difficult. However, water levels along the Great Lakes can fluctuate over one meter in a decade. Hands (1976, 1979, and 1980) and Weishar and Wood (1983) have demonstrated that the Bruun Rule generally predicts the erosion resulting from rises in water levels there.

The Bruun Rule has been applied to project erosion due to sea level rise for several areas of the United States where it is believed to adequately project future erosion. Bruun (1962) found that a 1-cm rise in sea level would generally result in a 1-m shoreline retreat, but that the retreat could be as great as 10 m along some parts of the Florida coast. Everts (1985) and Kyper and 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 m. The U.S. Army Corps of Engineers (1979) indicated that along the coast of San Francisco, where waves are generally larger than along the Atlantic Coast, the shore might retreat 2-4 m for a 1-cm rise in sea level.

Dean and Maurmeyer (1983) generalized the "Bruun Rule" approach to consider the "overwash" of barrier islands. Geologists basically believe that coastal barriers can maintain themselves in the face of slowly rising sea level through the landward transport of sand, which washes over the island during storms, building the island upward and landward. Because this formulation of the Bruun Rule extends the beach profile horizontally to include the entire islands as well as the active surf zone, it always predicts greater erosion than the Bruun Rule. However, the formulation may not be applicable to developed barrier islands, where the common practice of public officials is to bulldoze sand back onto the beach after a major storm.

The potential erosion from a rise in sea level could be particularly important to recreational beach resorts, which include some of the world's most economically valuable and intensively used land. Relatively few of the most densely developed resorts have beaches wider than about 30 m at high tide. Thus, the rise in relative sea level of 30 centimeters projected in the next 40 to 50 years could erode most recreational beaches in developed areas, unless additional erosion response measures are taken.

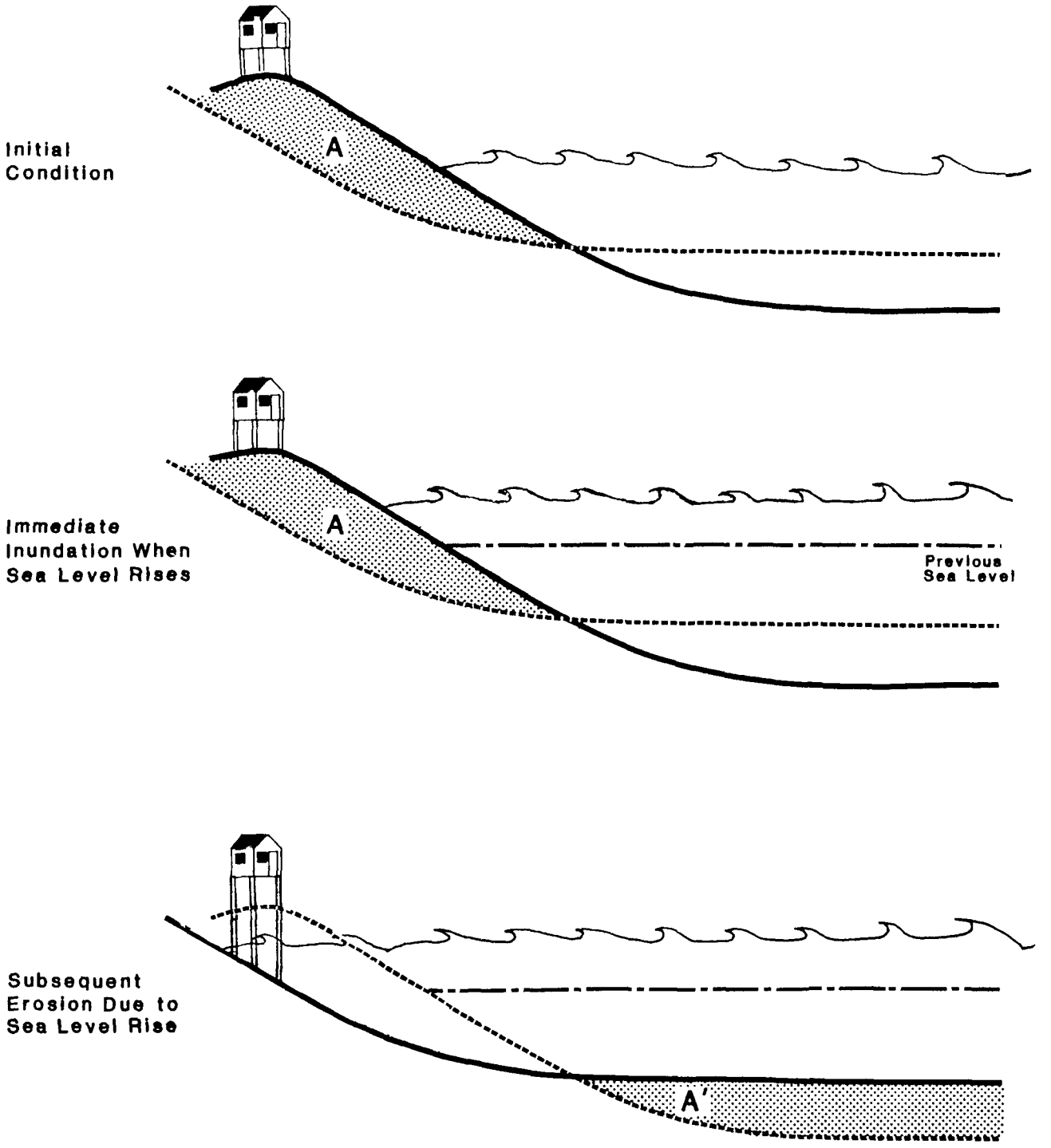

Figure 3. The Bruun Rule

Bruun (Volume 4) examines potential responses to erosion in considerable detail (see also Magness 1984; U.S. Army Corps of Engineers 1977). The responses fall generally into three categories: construction of walls and other structures, the addition of 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 in many areas (Kyper and Sorensen 1985; Howard, Pilkey, and Kaufman 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, Weisman, and Lennon 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 kilometer (U.S. Army Corps of Engineers 1980; Howard, Pilkey, and Kaufman 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. Sea level rise was cited as the motivating concern for 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 by a distance equal to shoreline recession from 30 years of erosion, while high-rises must be set back 60 years.[4] Maine requires people to demonstrate that new structures will not erode for 100 years.[5] Other jurisdictions discourage the construction of bulkheads and seawalls (Howard, Pilkey, and Kaufman 1985). As Bird (Volume 4) discusses, in many undeveloped countries, small, relatively inexpensive houses are found very close to the shore. Because the value of these houses is less than the cost of protecting them, they must be moved as the shore erodes. An accelerated rise in sea level would speed this process of shoreline retreat.

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

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[4] North Carolina Administrative Code, Chapter 7H, 1983. Raleigh, North Carolina: Office of Coastal Management.

[5] Fred Michaud, Office of Floodplain Management, State of Maine, personal communications.

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 most cost effective.

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 projects proposed to control erosion, most of which have historically been funded through the Army Corps of Engineers in the United States. 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. Gibbs estimated that the damage from a 100-year storm would be tripled for a rise of 88 cm.

A wide variety of shore protection measures would be available for communities to protect themselves from increased storm surge and wave damage due to sea level rise (Sorensen, Weisman, and Lennon 1984). Many of the measures used to address erosion and inundation, including seawalls, breakwaters, levees, and beach restoration, also provide protection against storms. In the case of Galveston, which is already protected on the ocean side by the seawall, Gibbs hypothesized that it might be necessary to completely encircle the developed areas with a levee to prevent flooding from the bay side; upgrading the existing seawall might also be necessary.

Kyper and Sorensen (1985 and n.d.) examined the implications of sea level rise for the design of coastal protection works at Sea Bright, New Jersey, a coastal community that currently is protected by a seawall and has no beach. Because the seawall is vulnerable to even a 10-year storm, the U.S. Army Corps of Engineers and the State of New Jersey have been considering a possible upgrade. Kyper and Sorensen estimated that the cost of upgrading the seawall

for current conditions would be $3.5 to $6 million per kilometer of shoreline, noting that if designed properly, the seawall would be useful throughout the next century. However, they estimated that a rise in relative sea level of 30-40 cm would be likely to result in serious damage to the seawall during a major storm, due to higher water levels and the increased wave heights resulting from the erosion of submerged sand in front of the seawall. To upgrade the seawall to withstand a 1-m rise in relative sea level would cost $5.7 to $9 million per kilometer (50 percent more). They concluded that policy makers would have to weigh the tradeoff between the cost of designing the wall to withstand projected sea level rise and the cost of subsequent repairs and a second overhaul.

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 occurred. 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 30 years; and setting premiums according to the average risk expected over the lifetime of the mortgage (Howard, Pilkey, and Kaufman 1985; Titus 1984).

Kuo (Volume 4) describes case studies in Charleston, South Carolina, and Fort Walton Beach, Florida, which 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 (with no storm surge) would result in no damages for the Gap Creek watershed in Fort Walton Beach. However, a rise in sea level of 30-45 cm would result in damages of $1.1 to $1.3 million 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 (n.d.), 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. 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 will 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 salt water could be important in some areas.

As de Sylva (Volume 4) describes, 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 salt water 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 and other river deltas, saltwater intrusion is causing the conversion of cypress swamps (which cannot tolerate salt water) to openwater lakes, and increasing the salinity levels of fresh and intermediate marshes. Accelerated sea level rise would speed up 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, Thatcher, and Tortoriello (1986) examined the potential impacts of an accelerated rise in sea level due to the greenhouse warming. They estimated that 73-cm and 250-cm rises would result in the salt front migrating an additional 15 and 40 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, respectively, and that the EPA drinking water 250-ppm chloride standard would be exceeded over 35 percent of the time in the latter case.

Lennon, Wisniewski, and Yoshioka (1986) examined the implications of increased estuarine salinity for the Potomac-Raritan-Magothy aquifer system, which is recharged by the (currently fresh) Delaware River and serves the New Jersey suburbs of Philadelphia. During the 1960s drought, river water with chloride concentrations as high as 150 ppm recharged these aquifers. Lennon et al. estimated that a repeat of the 1960s drought with a 73-cm rise in sea level would result in river water with concentrations as high as 350 ppm recharging the aquifer, and that during the worst month of the drought, over one-half of the water recharging the aquifer system would have concentrations greater than 250 ppm. With a 250-cm rise, 98 percent of the recharge during

the worst month of the drought would exceed 250 ppm, and 75 percent of the recharge would be greater than 1000 ppm.

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 (30-cm) 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 suggested that, given the uncertainties, it might be advisable today to identify additional reservoir sites, to ensure that future generations retained the option of building additional reservoirs, if necessary.

A rise in sea level could increase salinities in other areas, although the importance of those impacts has not been investigated. Kana et al. (1984) and Leatherman (1984) made preliminary inquiries into the potential impacts on coastal aquifers around Charleston and Galveston, respectively. However, they concluded that in-depth assessments were not worthwhile because the aquifers around Charleston are already salt-contaminated because of over-pumping, and pumping of ground water has been prohibited in the Galveston area as it causes land subsidence. The potential impacts on Florida's Everglades and the shallow aquifers around Miami might be significant, but these have not been investigated.

Economic Significance of Sea Level Rise

Only two studies have estimated a dollar value of the likely impacts of sea level rise for particular nations. Broadhus et al. (Volume 4) examine the impacts on Egypt and Bangladesh. Schneider and Chen (1980) estimated the economic impact on the United States of what was once (but is no longer) thought to be a plausible scenario: rises of 4.6 to 7.6 meters (15 to 25 feet) occurring with little or no warning during the early part of the twenty-first century. They estimated that these scenarios would result in real property losses of $100 to $150 billion, representing 6.2 to 8.4 percent of all real property in the nation.

The only comprehensive attempt to place a dollar value on the impacts of sea level rise for particular communities was the study by Gibbs (1984) of the Charleston and Galveston areas, summarized in Volume 4. Gibbs' analysis, which considers scenarios ranging from 0.9- to 2.4-meter rises through 2075, estimates what the economic impact would be if actions are taken in anticipation of sea level rise versus the cost of responding to sea level rise as it occurs. Gibbs also modeled how investment decisions might respond to floods and erosion, and explicitly considered community-wide strategies to limit losses, including shore protection and abandonment.

In the Charleston study, Gibbs assumed that in anticipation of sea level rise, efforts would be made to avoid developing some vacant suburban areas likely to be flooded in the future; that a partial abandonment would take place; and that the existing seawalls protecting Charleston would be elevated to provide additional protection. For a rise of 28-64 cm through 2025, Gibbs estimated that the present value of the cumulative impact would be $280-1065 million (5-19 percent of economic activity in the area for the period), which

could be reduced to $160-420 million if sea level rise was anticipated. Most of this impact would result from a 10-100 percent increase in expected storm damages, although Gibbs also estimated $7-$35 million in losses as a result of erosion. For the period 1980-2075, Gibbs estimated that the economic impacts would be $1250 - $2510 million (17 - 35 percent) and could be reduced to $440 - $1100 million through anticipatory measures. Gibbs performed a similar analysis of the Galveston area, concluding that the impacts of sea level rise through 2025 would represent $115 - $360 million (1.1 - 3.6 percent) if not anticipated, and $80 - $140 million if anticipated.

Other studies can be used to understand the economic significance of particular classes of impacts. As discussed above, a thirty-centimeter (one foot) rise in sea level would erode most recreational beaches back to the first row of houses. The studies cited in our section on erosion indicate that the typical beach profile extends out about 1000 meters, implying that 300,000 cubic meters of sand per kilometer of shoreline are required to raise the beach profile 30 cm. If sand costs are typically $3-$10 per cubic meter, the beach rebuilding costs of a 30-cm rise in sea level would be $1 - $3 million per kilometer. If the United States has a few thousand kilometers of recreational beaches, then it would cost billions and perhaps tens of billions of dollars to rebuild these beaches in response to a 30-cm rise in sea level. This estimate considers only the beaches themselves; raising people's lots to avoid inundation would further increase the costs. The U.S. Army Corps of Engineers (1971) estimated that in 1971, 25,000 kilometers of shoreline (exclusive of Alaska, the Great Lakes, and Hawaii) were eroding, of which 17 percent were "critically eroding," and would require engineering solutions. If 17 percent of all shorelines require erosion control, that would imply protection of close to 10,000 kilometers of shoreline. Sorensen (1986) describes dozens of engineering options for preventing erosion, the least expensive of which costs $300,000 per kilometer, implying a cost of at least $3 billion for protecting shorelines.

Other Impacts of the Greenhouse Warming

The impacts of sea level rise on coastal areas, as well as their importance, are 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, as Manabe and Wetherald describe in the next paper.

One of the more certain impacts is that most areas will be warmer. For coastal resorts in mid latitudes, 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 have more tolerable water temperatures in the future. Warmer temperatures in general might encourage more people to visit beaches in the summer.

Warmer temperatures might change the ability of wetlands to keep pace with sea level rise. Mangrove swamps, which are the tropical equivalent of salt marshes, generally accrete differently than salt marshes. If warmer temperatures enable mangroves to grow at higher latitudes, the loss of wet-

lands to sea level rise may be altered. On the other hand, marsh peat formation is generally greater in cooler climates; warmer temperatures might reduce the rate of vertical accretion for these wetlands.

De Sylva (Volume 4) suggests that changing climate could alter the frequency and tracks of storms. Because hurricane formation requires water temperatures of 27°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, it is generally recognized that a global warming would result in increased rainfall worldwide. Thus, rainwater flooding might be increased because of both 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 (Rind and Lebedeff 1984).

CONCLUSIONS

The studies reviewed in this paper appear to support the following conclusions regarding the causes and effects of sea level rise:

Causes

- The projected global warming would accelerate the current rate of sea level rise by expanding ocean water, melting alpine glaciers, and eventually, causing polar ice sheets to melt or slide into the oceans.

- Global average sea level has risen 10 to 15 cm over the last century. Ocean and glacial studies suggest that the rise is consistent with what models would project, given the 0.4°C warming of the past century. However, no cause and effect relationship has been conclusively demonstrated.

- Projected global warming could cause global average sea level to rise 10 to 20 cm by 2025 and 50 to 200 cm by 2100. Thermal expansion could cause a rise of 25 to 80 cm by 2100; Greenland and alpine glaciers could each contribute 10 to 30 cm through 2100. The contribution of Antarctic deglaciation is likely to be between 0 and 100 cm; however, the possibilities cannot be ruled out that (a) increased snowfall could increase the size of the Antarctic ice sheet, thereby offsetting part of the sea level rise from other sources; or (b) meltwater and enhanced calving of the ice sheet could increase the contribution of Antarctica to as much as two meters.

- Disintegration of the West Antarctic Ice Sheet might raise sea level an additional six meters over the next few centuries. Glaciologists generally believe that such a disintegration would take at least three hundred years, and probably as long as five hundred years. However, a global warming

might result in sufficient thinning of the Ross and Filcher-Ronne ice shelves in the next century to make the process irreversible.

- Local trends in subsidence and emergence must be added or subtracted to estimate the rise at particular locations.

Effects

- A substantial rise in sea level would permanently inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

- Bangladesh and Egypt appear to be among the nations most vulnerable to the rise in sea level projected for the next century. Up to 20 percent of the land in Bangladesh could be flooded with a two meter rise in sea level. Although less than 1 percent of Egypt's land would be threatened, over 20 percent of the Nile Delta, which contains most of the nation's people, would be threatened.

- A large fraction of the world's coastal wetlands may be lost, threatening some fisheries. A rise in sea level of one to two meters by 2100 could destroy 50-80 percent of U.S. coastal wetlands. Although no study has been taken to estimate the worldwide impact, this result is probably representative.

- Erosion caused by sea level rise could threaten recreational beaches throughout the world. Case studies have concluded that a thirty-centimeter rise in sea level would result in beaches eroding twenty to sixty meters or more. Because the first row of houses or hotels is often generally less than twenty meters from the shore at high tide, if available studies are representative, then recreational beaches throughout the world would be threatened by a thirty-centimeter rise unless major beach preservation efforts are undertaken.

- Sea level rise would increase the costs of flooding, flood protection, and flood insurance in coastal areas. Flood damages would increase because higher water levels would provide a higher base for storm surges; erosion would increase the vulnerability to storm waves; and decreased natural and artificial drainage would increase flooding during rainstorms.

- Future sea level rise may already be an appropriate factor to consider in the designing coastal drainage and flood protection structures.

- Increased salinity from sea level rise would convert cypress swamps to open water and threaten drinking water supplies.

- The adverse impacts of sea level rise could be ameliorated through anticipatory land use planning and structural design changes.

- Other impacts of global warming might offset or exacerbate the impacts of sea level rise. Increased droughts might amplify the salinity impacts of sea level rise. Increased hurricanes and increased rainfall in coastal areas could amplify flooding from sea level rise. Warmer temperatures

might enable mangrove swamps--which accrete differently than salt marshes--to advance further north, perhaps changing wetland loss caused by sea level rise.

- River deltas throughout the world would be vulnerable to a rise in sea level, particularly those whose rivers are dammed or leveed.

- Economic studies of Bangladesh, Egypt, and the United States suggest that sea level rise would be economically important to coastal areas.

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Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide[1]

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ABSTRACT. The geographical distribution of the change in soil wetness in response to an increase in atmospheric carbon dioxide was investigated by using a mathematical model of climate. Responding to the increase in carbon dioxide, soil moisture in the model would be reduced in summer over extensive regions of the middle and high latitudes, such as the North American Great Plains, western Europe, northern Canada, and Siberia. These results were obtained from the model with predicted cloud cover and are qualitatively similar to the results from several numerical experiments conducted earlier with prescribed cloud cover.

In assessments of the possible change in climate caused by the increasing CO_2 in the atmosphere, major emphasis has been placed on estimating the change in atmospheric temperature. However, for agricultural planning, the change in soil wetness may be just as important. In this study, which is a continuation of earlier studies (Manabe, Wetherald, and Stouffer 1981; Manabe and Wetherald 1985), CO_2-induced changes in soil wetness were investigated using a mathematical model of climate in which cloud amount is a predicted variable. Because of the large temporal variability of the model hydrology, it has been difficult to distinguish the CO_2-induced change from the natural variability of soil wetness. Therefore, the earlier reports discussed mainly the zonal mean rather than the geographical distribution of soil wetness. To overcome this difficulty, it is necessary to determine soil wetness of the model averaged over a very long period. The present study represents an attempt to extract the geographical distribution of soil wetness by substantially extending the average period.

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The mathematical model of climate used for this research is an atmospheric general circulation model coupled with a static mixed-layer ocean model[2]. The model has a global computational domain, realistic geography, and seasonally varying isolation.

Precipitation is computed whenever supersaturation is indicated by the prognostic equation for water vapor (Manabe, Smagorinsky, and Stickler 1965). It is identified as snowfall when the air temperature near the surface falls below freezing; otherwise it is identified as rain. The moist convective processes are parameterized by a moist convective adjustment scheme (Manabe, Smagorinsky, and Strickler 1965). Cloud cover is predicted whenever the relative humidity exceeds a certain critical value, which is 99% in this case. The distribution of cloud cover thus determined is used for the computation of solar and terrestrial radiation (Wetherald and Manabe 1980).

A change in snow depth is computed as a net contribution from snowfall, sublimation, and snowmelt that is determined from the requirement of surface heat balance (Manabe 1969). The budget of soil moisture is computed by the so-called bucket method (Manabe 1969). For simplicity it is assumed that soil can hold 15 cm of liquid water.[3] When soil is not saturated with water, the change in soil moisture is predicted as a net contribution of rainfall, evaporation, and snowmelt. If the bucket is full, the excess water is regarded as runoff. The rate of evaporation from the soil surface is determined as a function of the water content of the bucket and potential evaporation.[4]

The mixed-layer model of the ocean is idealized as a 50-m thick, vertically isothermal layer of water with predicted sea ice (Manabe and Stouffer 1980). The effects of horizontal heat transport by ocean currents and heat exchange between the mixed layer and the deeper layer of the ocean are neglected.

Two separate experiments were performed, one with the normal atmospheric concentration of CO_2 (300 ppm), and the other with twice the normal value (600 ppm). By comparing the results from the two experiments, the CO_2-induced change in hydrology could be determined. In each experiment a numerical 40-year integration of the model was conducted starting from an isothermal

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2 The thickness of the mixed-layer model of the oceans was chosen so that the amplitude of the observed seasonal variation of sea-surface temperature was approximately reproduced by the model (Manabe and Stouffer 1980).

3 The moisture-holding capacity of soil is assumed to be constant everywhere in view of our ignorance of its geographical distribution. According to unpublished results from a recent numerical experiment, the simulated distribution of soil moisture expressed as a fraction of the moisture-holding capacity of soil is not very sensitive to the magnitude of the field capacity.

4 Potential evaporation is the evaporation that would occur were there an adequate soil moisture supply at all times. According to M. Budyko (1974) potential evaporation is approximately equal to the total radiative energy absorbed by continental surfaces.

initial condition. Toward the end of this period, the temporal variation of the global mean sea-surface temperature of the model no longer had a systematic trend, indicating that the model had attained an equilibrium climate. To distinguish the CO_2-induced change from the natural variability of the model hydrology, the results were averaged over a sufficiently long period, i.e., the last 10 years of the 40-year integration. It is encouraging that, in the experiment with the normal CO_2 concentration, the model successfully reproduced the broad-scale features in the geographical distributions of precipitative and annual mean runoff.

The geographical distribution of the CO_2-induced change in soil moisture during June to August is illustrated in Figure 1A. In summer the soil becomes drier in the mid-continental region of North America, western Europe, and Siberia in response to the doubling of atmospheric CO_2.

The reduction in soil moisture in North America, western Europe, and Siberia is statistically significant at the 10% level (Figure 1B).[5] In other words, the probability of falsely rejecting the null hypothesis of no change in soil moisture is 10% or less in these regions.

To demonstrate the practical implication of the CO_2-induced summer dryness identified above, the change in soil moisture was expressed as a percentage of the soil moisture from the normal CO_2 experiment (Figure 1C). This result suggests that the CO_2-induced reduction in soil moisture in the mid-continental regions of North America, Siberia, and western Europe amounts to a substantial fraction of the soil moisture present in the standard CO_2 case.

In general, the soil moisture in the model continents in middle and high latitudes is reduced from the peak level in spring to the minimum level in summer. In high latitudes, this spring-to-summer reduction in moisture is caused by intense evaporation in late spring, when the continental surface absorbs a large amount of solar energy because of strong insolation and the disappearance of snow cover with high albedo. In middle latitudes a similar mechanism also operates over the model continents. In addition, the reduction in soil moisture from spring to summer in middle latitudes is caused by the termination of the rainy period in spring that results from the poleward shift of the rain belt.

According to the comparison of the surface water budget between the normal and high CO_2 experiments, the CO_2-induced reduction in soil moisture in summer in Siberia and northern Canada is a result of the earlier disappearance of snow cover in the warmer climate. Since the snow cover has a high surface albedo, its disappearance increases the surface absorption of solar energy and accordingly increases the rate of potential evaporation (Budyko 1974). Thus, the earlier termination of the snowmelt season results in the earlier

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5 Student's t test was used. For this test, ten samples of summer soil moisture were obtained from the last 10-year periods of normal and above-normal CO_2 experiments conducted in this study. Because each sample represents an average of ninety daily soil moistures, it is likely that these samples are distributed approximately as Gaussian (as inferred from the central limit theorem), justifying application the of this test.

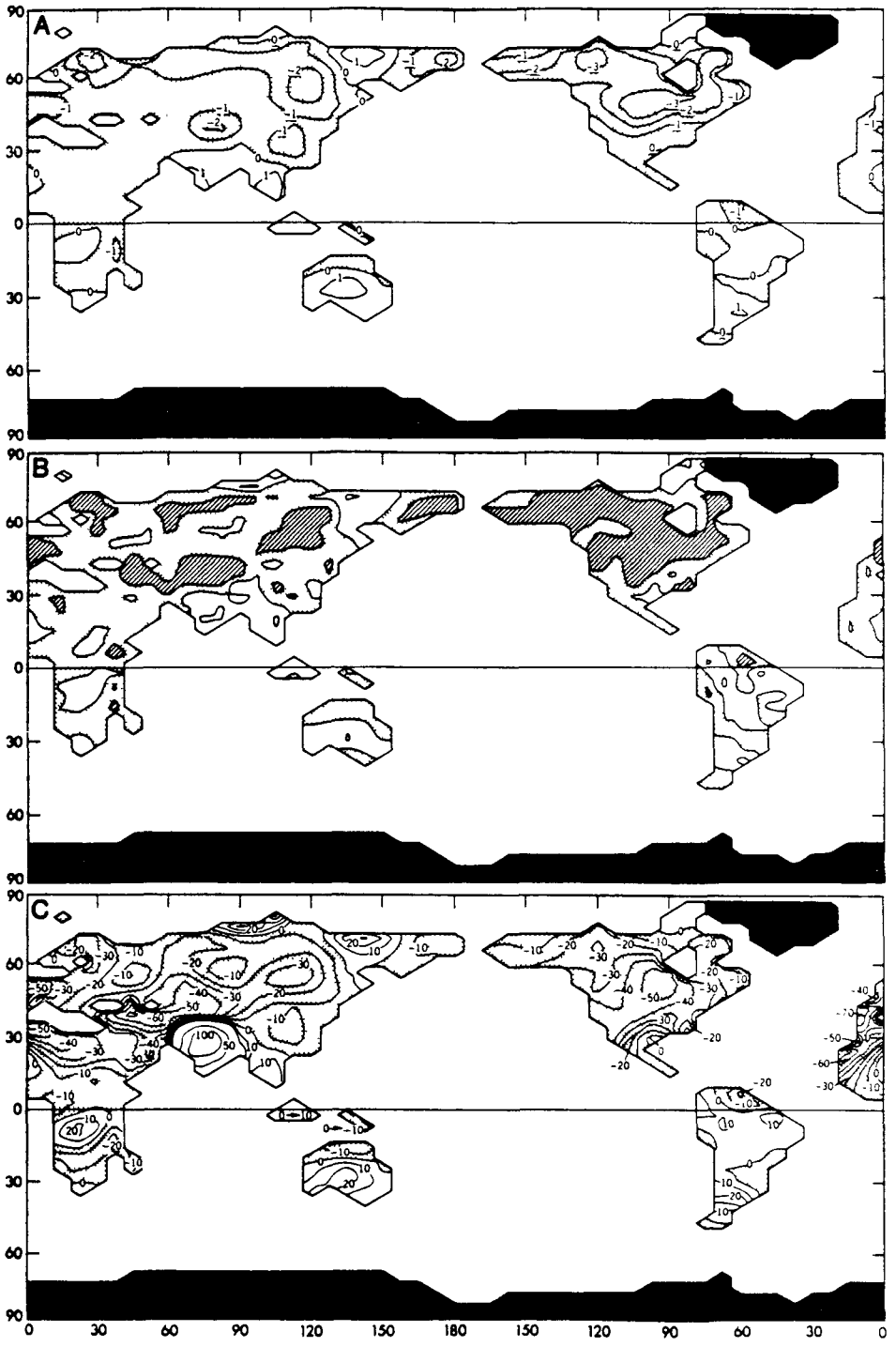

Figure 1. (A) Geographical distribution of the change in soil moisture (centimeters) in response to a doubling of CO_2 for the period from June to August. Shading indicates regions where the CO_2-induced change is negative. (B) Statistical significance of the CO_2-induced change in soil moisture shown in (A). Areas shaded with lines are regions where the negative soil moisture change is statistically significant at the 10% level. (C) CO_2-induced change in soil moisture expressed as a percentage of soil mositure obtained from the normal CO_2 experiment.

commencement of the spring-to-summer reduction in soil moisture, causing the CO_2-induced reduction in soil moisture in summer.

In the Great Plains the earlier termination of the snowmelt season also contributes to the summer CO_2-induced reduction in soil moisture. Another factor responsible for the summer reduction is the change in the rate of precipitation in middle latitudes. The CO_2-induced warming in the lower troposphere in the model increases with increasing latitude. Therefore, in the high CO_2 atmosphere the warm, moisture-rich air penetrates into higher latitudes than in the normal CO_2 atmosphere. Thus the rate of precipitation increases markedly in the northern half of the middle latitude rain belt of the Northern Hemisphere, whereas it decreases in the southern half of the rain belt. Because of the poleward shift of the rain belt from winter to summer, a location in middle latitudes which is situated at the northern half of the rain belt during winter enters the southern half in summer. Therefore, the CO_2-induced increase in rate of precipitation at this location is rapidly reduced from spring to early summer, contributing to the reduction in soil moisture during this period.

In western Europe the CO_2-induced reduction in soil moisture occurs in summer in a manner qualitatively similar to that in North America. However, the contribution of snowmelt is much smaller.

The summer dryness in North America and western Europe is further enhanced by the positive feedback process involving the change in cloud cover. When soil moisture is reduced, a larger fraction of radiative energy absorbed by the continental surface is ventilated through the upward flux of sensible heat rather than through evaporation. As a result, the temperature of the continental surface and the overlying layer increases, causing the general reduction in relative humidity and precipitation in the lower troposphere of the model. Accompanying the reduction in relative humidity is a reduction in total cloud amount, causing an increase in solar energy reaching the continental surface. Thus, the radiation energy absorbed by the continental surface also increases, raising the rate of potential evaporation (Budyko 1974). Both the decrease in precipitation and the increase in potential evaporation further reduce soil moisture during early summer and help to maintain it at a low level throughout the summer.

During summer over the Great Plains total cloud cover is reduced and surface air temperature increases substantially in response to the doubling of the CO_2 concentration in the model atmosphere (Figure 2). Qualitatively similar but smaller changes in cloud cover and temperature also occur over western Europe. In summary, the positive feedback process involving cloud cover enhances the CO_2-induced summer dryness in the Great Plains and western Europe.

The seasonal variation of the change in zonal mean soil moisture caused by the CO_2 doubling is illustrated in Figure 3. In middle and high latitudes, zonal mean soil moisture over the continents declines substantially during summer months and is consistent with the geographical distribution of soil moisture change discussed above.

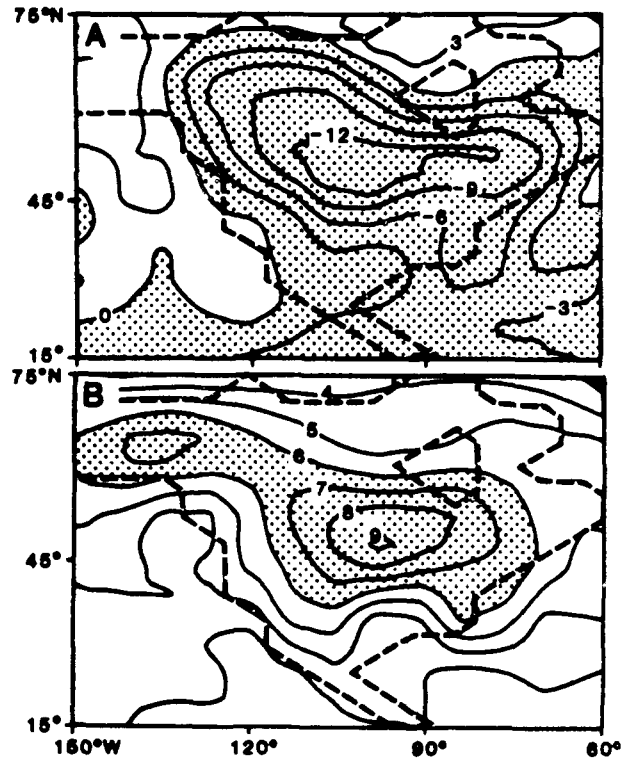

Figure 2. Geographical distributions of the changes in (A) total cloud amount (%) and (B) surface air temperature (°C) in response to a doubling of CO_2 content for June to August. Only the distributions in the neighborhood of the North American continent are illustrated.

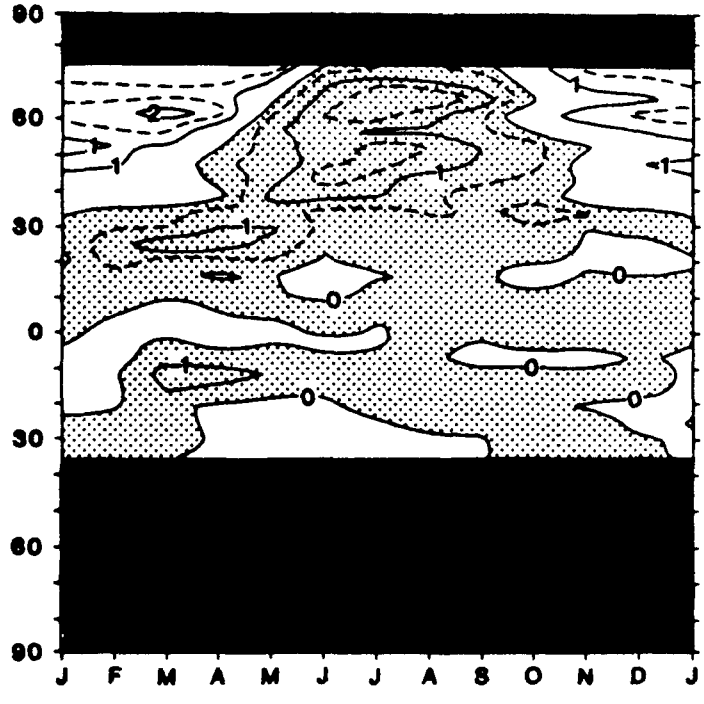

Figure 3. Latitude-time distribution of the change in zonal mean soil moisture (centimeters) over the continents of the model in response to a doubling of CO_2. Results are not shown for latitudes where open ocean dominates.

In winter, when the middle latitude rain belt is displaced toward the equator, soil wetness increases not only in high latitudes but also in middle latitudes. However, it is reduced at about 25°N, that is, in the southern half of the rain belt. Qualitatively similar changes of zonal mean soil moisture have been obtained previously (Manabe, Wetherald, and Stouffer 1981; Manabe and Wetherald 1985; Manabe and Stouffer 1980; Wetherald and Manabe 1981).

The results described above were obtained by using the model with predicted cloud cover. Similar experiments are also conducted by using another model with fixed cloud cover. A detailed analysis of these experiments also indicates the CO_2-induced reduction of soil moisture in summer, although the magnitude of the reduction is considerably smaller than that suggested here. These results suggest that the summer dryness in the mid-continental regions occurs despite the absence of the cloud feedback process. However, the cloud feedback process enhances the dryness.

In the subtropical portion of the continents in the Northern Hemisphere (such as the northern coast of Africa, central Asia, India, and Southeast Asia) the geographical distribution of the CO_2-induced change in soil moisture varies greatly from one experiment to another. Furthermore, these changes are not always statistically significant, partly because of the large natural variability of the model hydrology. Therefore, one should not take the changes in these regions too literally, pending further investigation. A similar caution applies to the geographical distribution of the CO_2-induced change in the soil moisture in the continents of the model in the tropics and the Southern Hemisphere.

It is tempting to speculate that the Dust Bowl drought of the 1930s may have been induced by a warm-climate anomaly. As noted by Vinnikov and Groismann (1982) the seasonal and latitudinal profiles of the positive anomaly of surface air temperature during the 1930s resemble the CO_2-induced warming obtained from the present experiments.

In the model the CO_2-induced global mean increase in surface air temperature with predicted cloud cover is about 4°C and is 1.5 to 2 times larger than the corresponding warming with prescribed cloud cover (Manabe and Stouffer 1980). This indicates that the cloud feedback process can enhance CO_2-induced increase in global mean surface air temperature, as suggested by Hansen et al. (1984). However, a recent study by Somerville and Remer (1984) suggests that the increase in the liquid water content of clouds in response to the warming of air may act as a negative feedback between temperature and cloud cover by increasing the planetary albedo, thereby reducing the sensitivity of climate. This effect is not considered in the model. In view of the primitive state of the art for the parameterization of cloud formation and other processes, the quantitative aspect of the present study should be interpreted with caution.

Despite these uncertainties, it seems significant that all the experiments discussed in this report indicate CO_2-induced summer reduction and winter enhancement of soil wetness over extensive, mid-continental regions in middle and high latitudes. Furthermore, the analysis of the soil moisture budget suggests that these large-scale changes in soil wetness are determined by the latitudinal and seasonal profiles of the CO_2-induced warming and do not

critically depend on the details of the warming. Therefore, it is likely that the basic conclusion is valid despite imperfections of the model.

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Effects of Climatic Changes on Agriculture and Forestry: An Overview

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INTRODUCTION

The purpose of this paper is to give an overview of the potential effects of climatic change on agriculture and forestry. We focus largely on long-term climate changes, particularly those likely to result from changes in the composition of the atmosphere. We do not distinguish climate change caused by natural factors from that caused by greenhouse gases; but we are concerned with evaluating the potential effects of the resultant climatic change, whatever its causes. We note at the outset that our concern here is with climatic change, not with the "direct" effects of changes in composition of the atmosphere (e.g., the enhancing effects of increased atmospheric carbon dioxide (CO_2) on plant growth). A strong case can be made that effective assessment of the potential effects of increased CO_2 requires both direct and indirect (climatic) effects be considered, but that case will not be further developed here.

In this paper, we first consider briefly the types of climate change that may affect agriculture and forestry. This discussion is followed by an outline of the impact that climatic changes are known to have had in the past and what we can learn from this experience. We then examine the methods that have been developed, quite recently in most cases, to assess the effects of climatic change. There is then some discussion of the results of a few recent assessments, particularly of the potential effects of CO_2-induced climatic changes on agriculture and forestry. The paper concludes with an indication of the present gaps in our knowledge and our future research priorities.

TYPES OF CLIMATIC CHANGE

Because different types of climatic change can have markedly different ecological and economic effects, it is important to distinguish them. First, we should distinguish between climatic noise, climatic variability, and climatic change [see Hare (1985) for further details]. We may use the term

climatic noise to refer to that part of the variance of the climate resulting from short-term weather changes. It includes, for example, anomalous weather extremes (such as floods and droughts) that can have a serious impact on agriculture. Climatic variability represents the manner of variation of the climatic parameters (e.g., their standard deviation, frequency, etc.) within the typical averaging period (normally 30 years). Climatic change refers to those differences between successive averaging periods that cannot be accounted for by noise.

Secondly, we should distinguish three types of climatic change [see Parry (1986) for further details]:

- Short-term, frequent changes to which social and economic systems are generally adjusted
- Medium-term climatic changes to which society probably needs to adapt to avoid undesirable impact
- Long-term climatic changes that occur on time scales too large to be considered significant for the planning horizons of most societies.

This classification may seem somewhat unusual because it is based not on the nature of the climatic changes, but on their impact. It may, however, be appropriate since our task is to assess impacts, not to explain them. We may pursue this line of argument further by identifying two additional perspectives on climatic changes, once again distinguished by their impact rather than by their nature. The first, termed by Warrich, Gifford, and Parry (1986) as the "slow change" view, emphasizes the significance of gradual increases in mean surface temperatures likely to result from increases in atmospheric CO_2. These can be expected to lead to gradual, long-term, and cumulative changes in average regional climates. Following this view, we might conclude that so long as we can predict the long-term climate trend, there need be no surprises in store for the farmer or forester who should have time to modify their practices accordingly.

The alternative view emphasizes the changes in the frequencies of unusually disruptive (or beneficial) events that may result from changes in climate. This view assumes that impact from climatic change comes not only from the average but also from the extreme event, a point that has been developed at some length elsewhere (Parry 1978, 1985). To illustrate, few farmers plan activities on their expectation of the average return. They gamble on good years and insure against bad ones (Edwards 1978). In general, we might expect subsistence farmers to tune their activities to bad years, attempting to minimize the impact of those years, while commercial farmers (such as those on the Canadian prairies) may tune them to good years [which is why the prairie farmer is periodically stressed when bad years prevail (McKay and Williams 1981)].

The impact from extremes can alter in a number of ways. To illustrate, let us assume that annual rainfall or temperature has a Gaussian (normal) distribution about the mean x and variance k^2. We also assume that agriculture is only seriously affected if rainfall or temperature is outside the range ($\bar{x} \pm k$) (Figure 1a). In the first type of change, $\bar{x}$ changes but

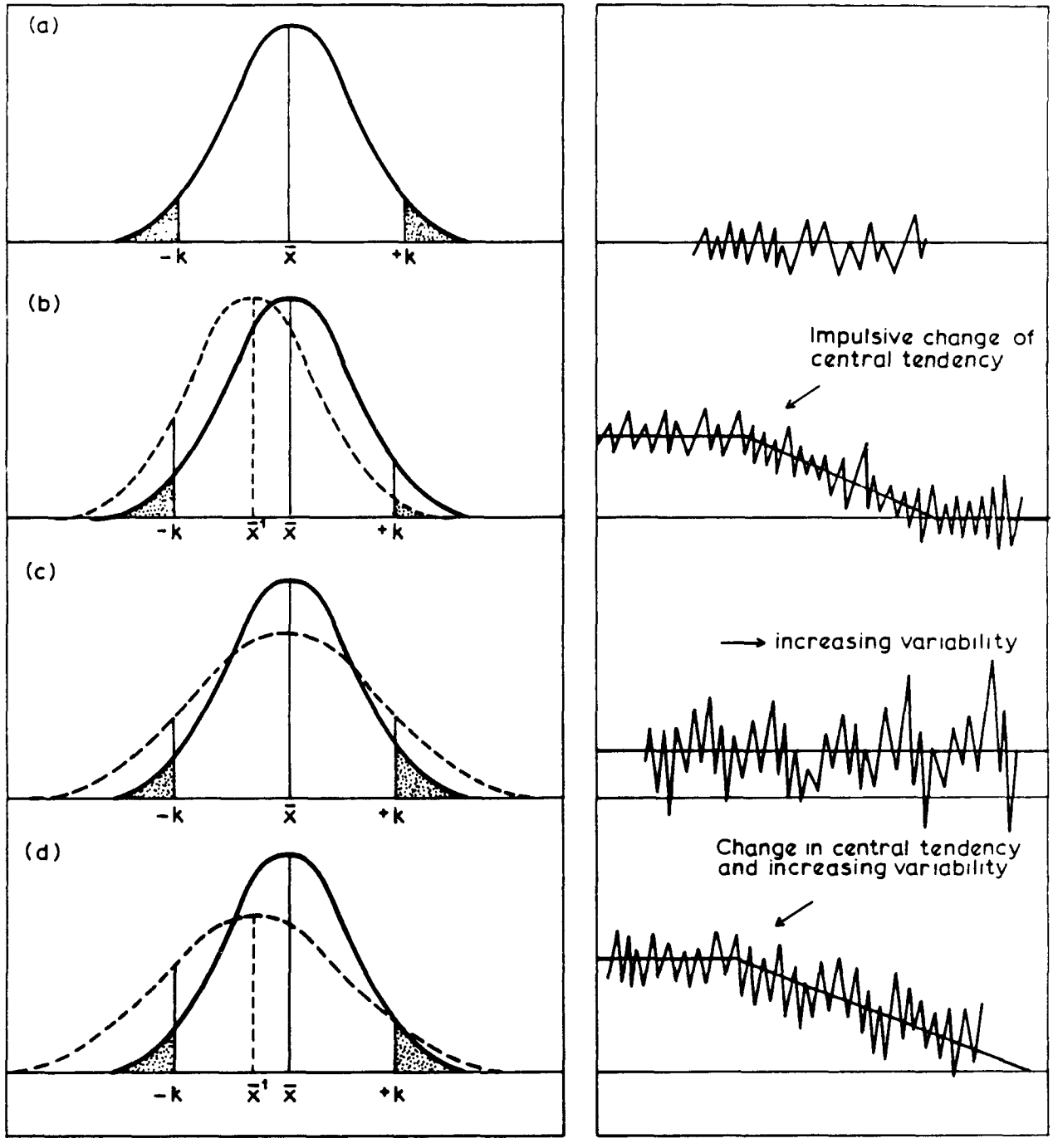


Figure 1. Changes in probability distributions and stochastic outcomes for shifts in mean, variance, or both. After Fukui (1979) and Hare (1985).

remains unchanged (Figure 1b). The frequency of negative extremes (as originally defined by the agricultural system which we assume to be slow to adapt to the new climate regime) is increased, and positive extremes are reduced. If this change occurred for rainfall on the Canadian prairies, we might expect the bad years to far exceed the good years. In the second type of climatic change, k changes but $\bar{x}$ does not (Figure 1c). There is increased risk of both deficient and excessive temperatures and/or rainfall. Both $\bar{x}$ and k change in the third type (Figure 1d).

HOW HAS THE CLIMATE CHANGED IN THE PAST?

Our intention here is to present a very brief summary of some of the changes in climate which we know to have occurred in the past [for more information, see Wigley, Ingram, and Farmer (1981)] to provide a backdrop for a later discussion of the effect of these changes on agriculture and forestry.

Changes on a Millenial Scale

If we take as our starting point the last glacial maximum (around eighteen thousand years ago), we may note that a rapid global warming began around thirteen thousand years ago, was interrupted around eleven thousand years ago by a sharp and severe cooling episode around 11,000 BP, and was then resumed (Wigley, Jones, and Kelly 1986) (Figure 2a). By about ten thousand years ago (the beginning of the so-called Holocene), global temperatures had roughly reached their present-day mean.

Changes on a Secular Time Scale

During the past two thousand years, the major changes that have occurred include the medieval warm epoch (800 to 1200 A.D.) and the Little Ice Age (ca. 1500 to 1800 A.D.) (Figure 2b). In western Europe mean annual temperatures at the nadir of the Little Ice Age were about 2°C lower than in the early medieval period. These estimates are based on a wide array of proxy data, including oxygen isotopes, harvest size and harvest dates, and dates of freezing and thawing of navigable rivers and lakes.

Decadal Changes

The instrumental record enables us to be more precise for periods after 1850. A long-term warming trend appears to have occurred, interrupted by cool episodes around 1900 and during the 1960s. Present-day mean surface temperatures have been broadly restored to their medieval levels. Figure 2c shows observed temperatures and the moving average from 1850 to the present.

HOW WILL THE CLIMATE CHANGE?

The following section is a brief summary of a recent synthesis of our present knowledge [for further detail, see Dickinson (1986)]. Our aim here is simply to indicate the direction and approximate scale of the changes that may occur and how these compare with changes experienced in the past. These may be summarized as follows (WMO 1986):

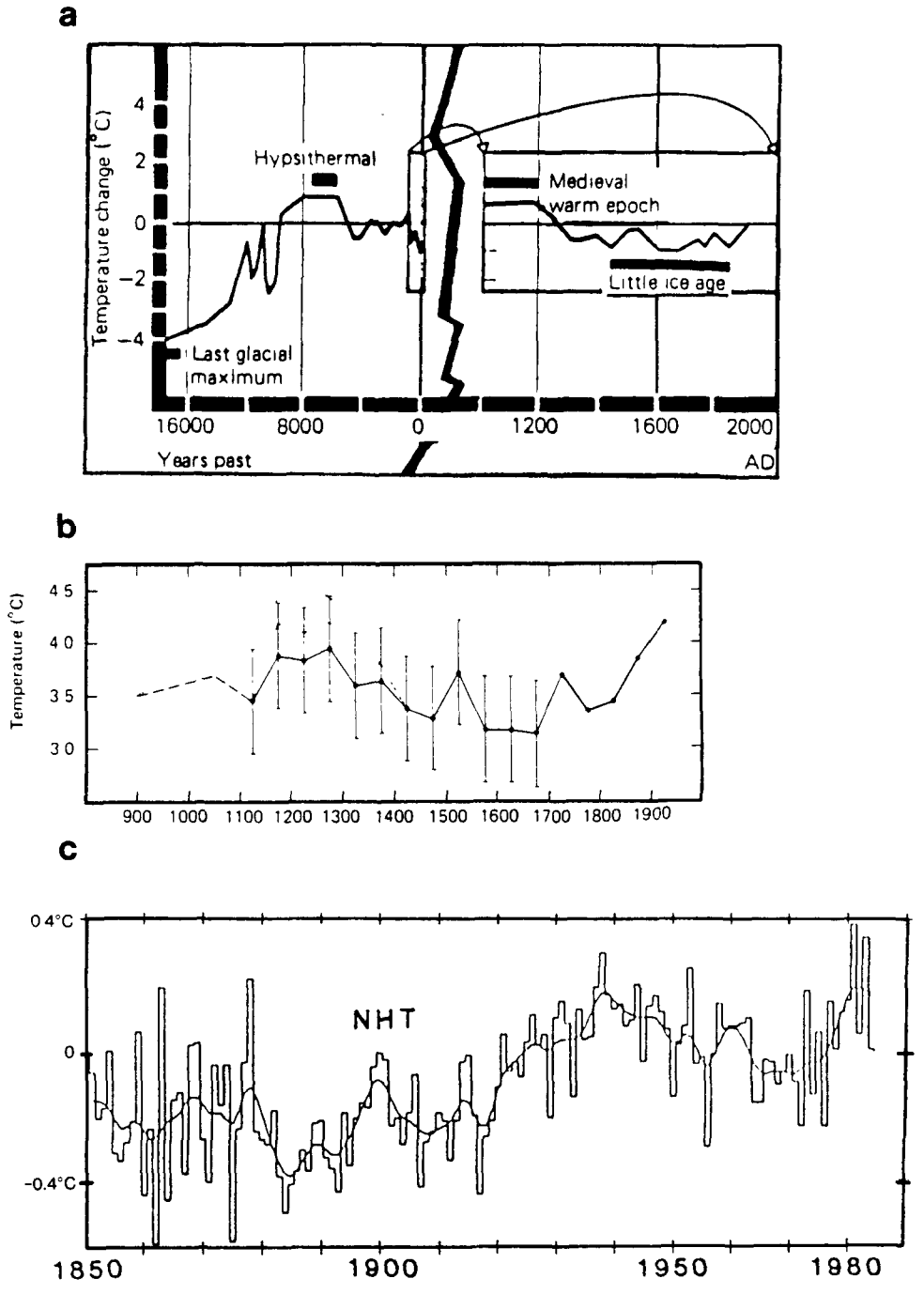


Figure 2. (a) schematic representation of temperature changes during the past 20,000 years (Wigley 1982); (b) 50-year averages of winter temperature for England. The continuous line gives unadjusted values based soley on regression analysis and Winter Severity index values prior to 1700. Ninety-five percent confidence limits based on the regression equations and using the t-distribution are shown. Values shown after 1700 (temperature) are observed instrumental data from Manley's central England temperature series (Manley 1974). The long dashed lines project the unadjusted estimates back in time, but only 100- to 200-year means are given based on sparse data. The short dashed line in the temperature curve gives adjusted values, accounting for botanical evidence. The dotted curve is the analyst's opinion based on a wide variety of evidence (Lamb 1981); (c) Northern Hemisphere annual mean surface temperatures from land-based record (Wigley et al. 1986).

- The change in global equilibrium temperature from increases of CO_2 and other trace gases equivalent to a doubling of CO_2 is expected to be in range of 1.5 to 5.5°C (Dickinson 1986). This change would be of the same order as that which occurred between the last glacial maximum and the Hypsithermal (Figure 2a). A doubling of CO_2 concentrations is expected to be reached between 2050 and 2100.

- The global warming up to the present suggested by models to result from previous increases of CO_2 and other trace gases is in the range of 0.3° to 1.1°C (WMO 1986). The observed increases in mean temperature during the last century "cannot be ascribed in a statistically rigorous manner to the increasing concentration of CO_2 and other greenhouse gases, although the magnitude is within the range of predictions" (WMO 1986).

- There are indications that warming will be enhanced in high latitudes and that summer dryness may become more frequent over the continents at middle latitudes in the Northern Hemisphere (WMO 1986).

EFFECTS OF CLIMATIC CHANGES IN THE PAST

In this section we review some of the effects that climatic changes have had on agriculture and forestry in the past. Our aim is to indicate some of the types of effects that have occurred and some of the adjustments that have proven successful, which provides a basis for considering potential impacts in the future and for identifying appropriate responses to them. We take a number of examples to illustrate the different kinds of climatic changes outlined in the section on types of climatic change, from single extreme events to long-term trends. The examples are arranged in research chronological order, moving from recent isolated extreme events to prehistoric long-term climatic changes.

The Effect of Isolated Extreme Events

Drought in the U.S. Corn Belt, August 1983. Midsummer 1983 saw a pronounced drought in the U.S. corn belt and the southeastern United States. U.S. maize yields fell by about a third, from over seven thousand kilograms per hectare to about five thousand kilograms per hectare (Figure 3). In the same year, however, the Payment-in-Kind Program (PIK) had encouraged large numbers of corn (maize) farmers not to plant in 1983 (as part of an effort by the USDA to reduce the national grain surplus). As a result, the U.S. area planted to maize also fell by about a third, from thirty to twenty-one million hectares (Figure 3). The combined effect of decreased yield and reduced area was a fall in U.S. maize production by almost one half (from 210 million metric tons in 1982 to 110 million metric tons in 1983) (Figure 3).

The effects were felt not only nationally, but also globally, because U.S. maize accounts for about one-eighth of the world's total marketed cereal production. World total cereals production in 1983 fell by 3 percent, harvested area by 1.4 percent, and yield by 2 percent, these reductions being almost fully accounted for by the U.S. figures alone (Figure 4).

USA MAIZE PRODUCTION, AREA HARVESTED AND GRAIN YIELD 1972–1983

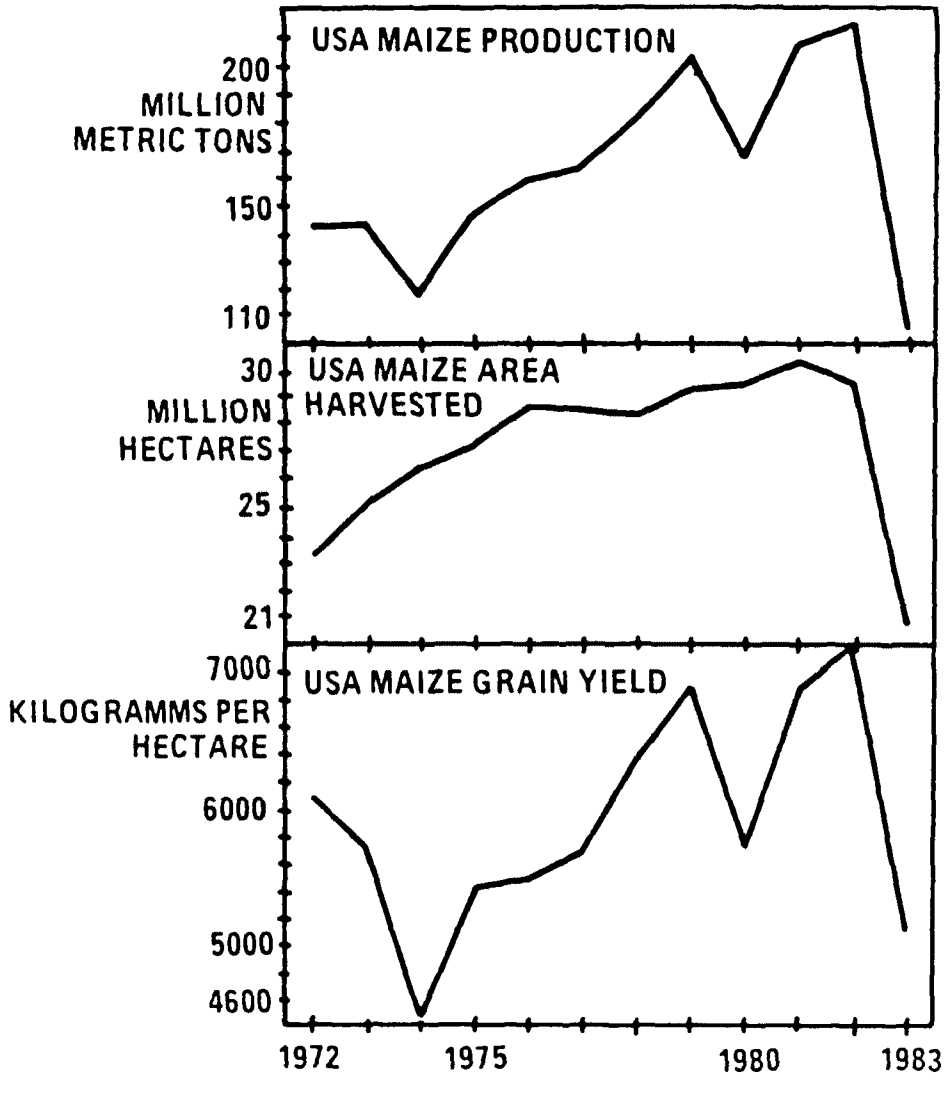


Figure 3. USA Maize Production, Area Harvested and Grain Yield 1972-83 (FAO).

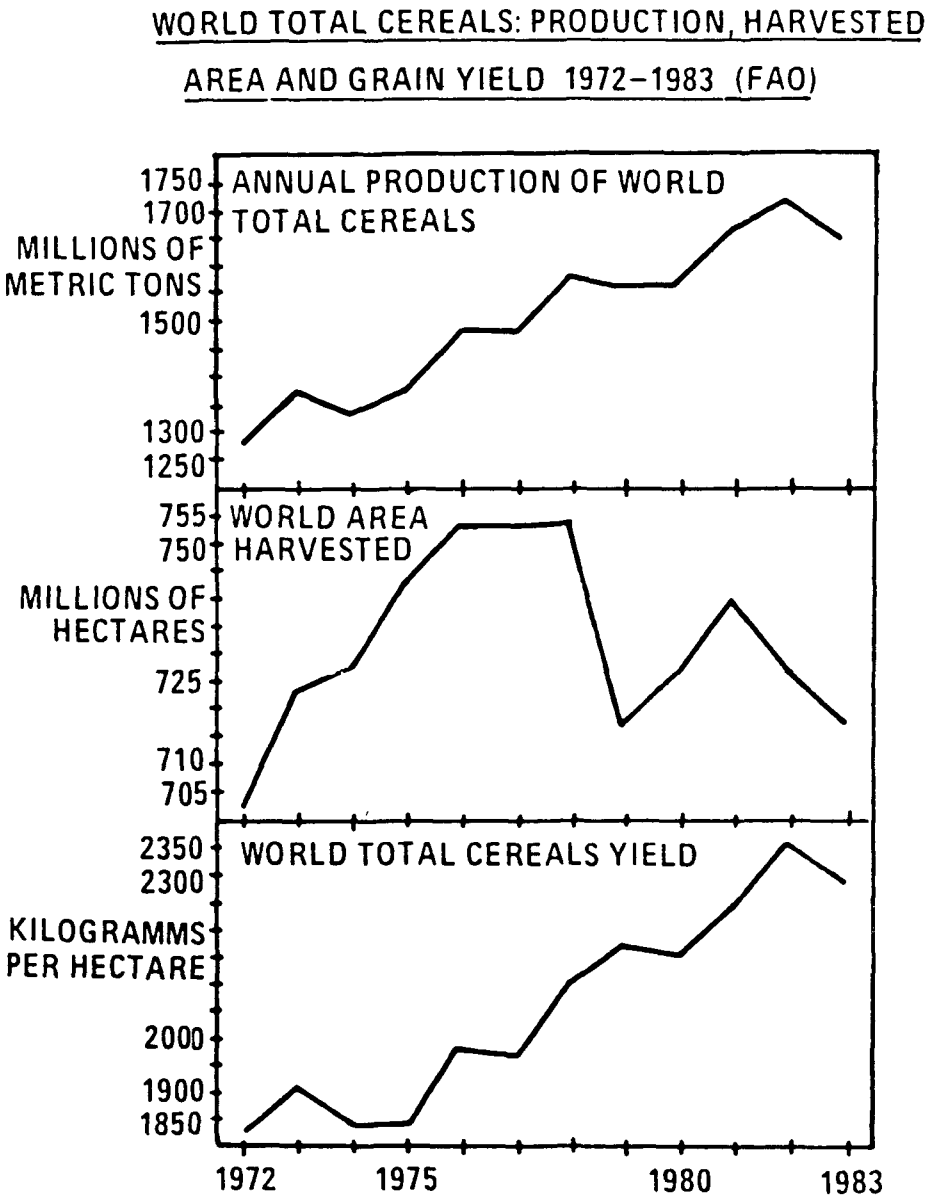


Figure 4. World Total Cereal Production, Harvested Area, and Grain Yield 1972-83 (FAO).

Drought in the United Kingdom, 1976. From May 1975 to August 1976 rainfall in the southeast of England was about 60 percent of normal (Doornkamp, Gregory, and Burn 1980). (No drier spell of comparable length appears on the 300-year instrumental record.) Almost all crops were affected. Nationally, potato yields were down 25 percent of the 1970-74 average and cereal yields 10 to 15 percent. Since planted area had not been substantially affected, falls in production were broadly commensurate: Potato production down 2.25 million tons and wheat down 2 million tons. The shortfall in cereal production required the import of around 1 million tons of cereal worth 80 million (British) pounds.

But prices responded accordingly. U.K. potato prices increased threefold over 1975-76 and wheat increased one third over 1976-77 from the previous year. As a result, aggregate net income of the agricultural industry rose in real terms by 7 percent from 1975 to 1976, with little change from 1976 to 1977. Certainly some farmers suffered (such as those engaged in livestock fattening in lowland areas where higher feed prices were not fully balanced by increased livestock prices), but the general message of the 1976 drought is that market reactions combined with sensitive government response in raising guaranteed prices can effectively buffer even the severest of climatic events. The problem really arises when government policy is insensitive to climate change, such as the U.S. Department of Agriculture's Payment-in-Kind program, which could not foresee that a massive yield downturn as a result of drought, in combination with reduced planting induced by government policy, could lead to reductions in production that were almost twice as large as those intended. Fortunately, U.S. corn yields were back up in the benevolent weather-year of 1984. But if 1984 had also been a drought year, the outcome could well have been a severe drop in national and global cereal food stocks. This leads us naturally to consider the dramatic effects that a series of climatic anomalies can have on agricultural production.

The Effect of Recurrent or "Back-to-Back" Climatic Events

Runs or sequences of anomalous weather-types tend to have a cumulative and compounding impact, the net effect being greater than the sum of the single extreme-year effects. Over 1932-37, for example, persistent drought in the U.S. Great Plains helped bring about approximately two-hundred thousand farm bankruptcies or involuntary transfers and the migration of more than three-hundred thousand people from the region. If the same weather were to occur today, assuming 1975 technology and a 1976 crop area, the impact would still be considerable. For a recurrence of the worst weather-year, 1936, simulated production shows a drop of 25 percent, reducing national wheat production by about 15 percent (assuming average production elsewhere in the USA) (Figure 5). The cumulative effect could be substantial: yearly yields simulated for the weather over the period 1932 to 1940 average about 9 to 14 percent below normal and amount to a cumulative loss over the decade equal to about a full year's production in the Great Plains (Warrich 1984).

The Effect of Secular Fluctuations of Climate

To assess the past effects of long-term changes of climate our subject matter becomes historical, and one problem confronting us is that there are few proofs in history: connections between climatic changes and economic

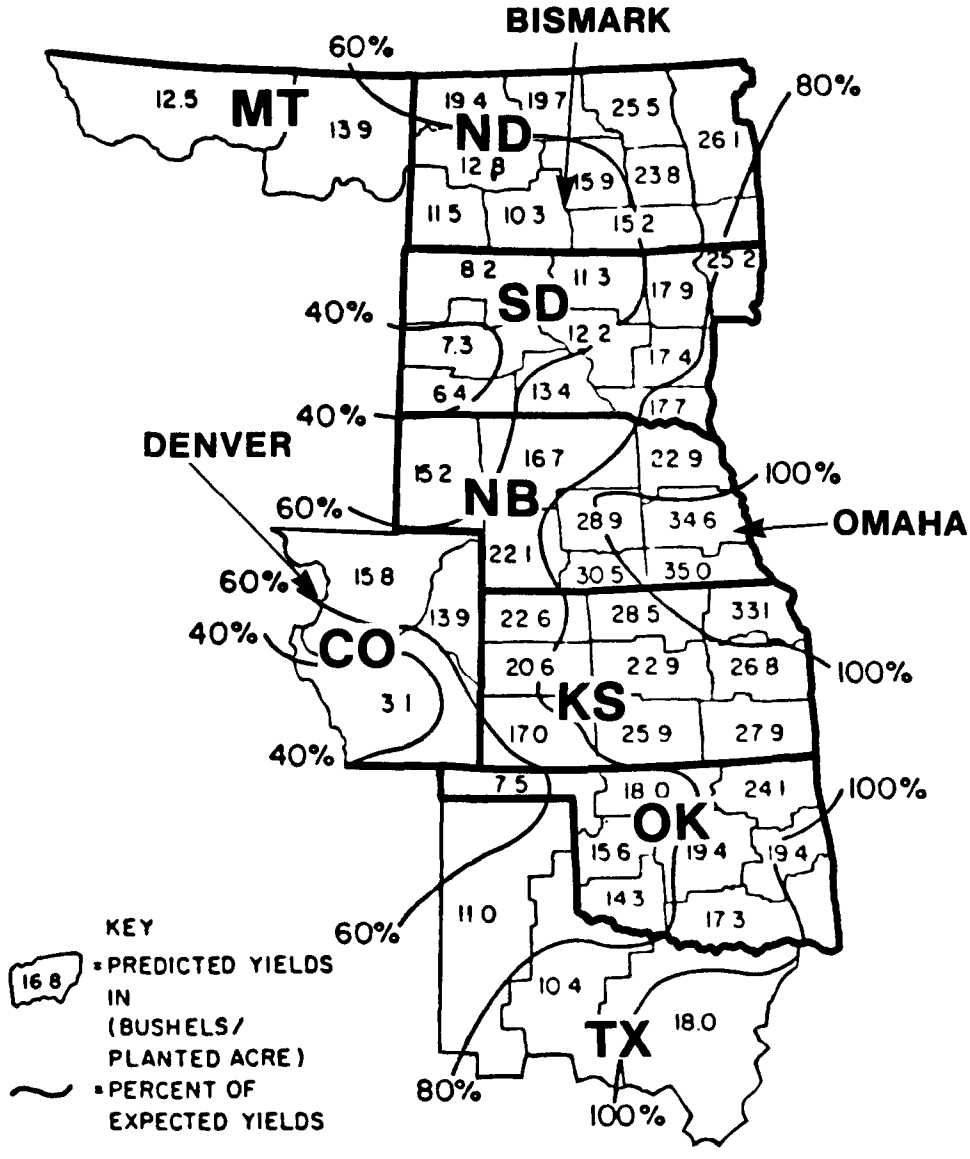


Figure 5. Simulated Wheat Yields on the Great Plains: 1936 Weather, 1975 Technology (Warrick 1984).

changes in the past depend on skilled but essentially qualitative interpretation. However, to illustrate the potential effects of secular climatic changes, we refer to one or two episodes during which the two events have been plausibly connected by historical scholarship.

The Little Ice Age in Western Europe 1500-1800. Between about 1500 and 1800 mean annual temperatures were about 1.5°C below that of the present norm and also that of the preceding warm epoch of A.D. 800 to 1200. At the nadir of this cold episode, the accumulated temperature of the growing season in southern Scotland was 10 percent less than at present (Parry 1978). There was a permanent snowfield in the Scottish highlands. Icebergs were reported to have drifted ashore carrying polar bears from the Arctic (Lamb 1982). There was widespread desertion of the more marginal upland settlements in Scotland. In Norway about half of the farms were abandoned in the late Middle Ages (Parry 1978). In Iceland the cultivation of cereals died out before 1600 AD. The period was clearly one of considerable difficulty for those farming near the northern limit of agriculture, but few historians would deny that even under these unusual climatic conditions there existed a range of adjustments that farmers could employ to respond and survive. Deserting settlements and moving somewhere else more attractive were simply some of the more radical forms of one response.

Late Medieval Cooling, 1250-1500. On the issue of adaptation the experience of Norse settlers in Greenland can be instructive. The Norse had gained a foothold along the Greenland coast in around 985, but their settlements had been completely abandoned at least by 1500, probably between 1350 and 1450. In the 13th century the population, which then totaled about six thousand in two settlements, was subjected to a synergistic interaction of stresses from hostile Eskimos (Inuit), the decline of the European market for walrus ivory, and challenging spells of cool summers and stormy winters, particularly around 1270-1300, 1320-1360, and 1430-1460. The failure to adapt to the changing circumstances is believed to explain much of the Norse decline (McGovern 1981). The Norse continued to emphasize stock raising in the face of reduced capacity of the already limited pastures. The option of exploiting the rich seas around them, as the Inuit successfully did, was not taken up, perhaps because of the inflexible attitude of priest-rulers in a highly stratified religious society:

> "Baldly put, a society whose administrators (as well as its peasants) believe that lighting more candles to St. Nicholas will have as much (or more) impact on the spring seal hunt as more or better boats is a society in serious trouble" (McGovern 1981).

According to McGovern, the Norsemen had lost some of the adaptiveness and resourcefulness that they displayed some three hundred years earlier at the time of the settlement. It is an extreme example of how governments can fail to identify and implement appropriate policies of response, not only to climatic change but to the synergistic effects of a number of concurrent events, and it serves to emphasize the value of designing policies that are responsive to the "package" of environmental issues currently facing us today--of increasing concentrations of greenhouse gases, acid deposition, desertification, groundwater pollution, salinization, deforestation, etc.--a package that requires an integrated set of policies.

METHODS IN CLIMATE IMPACT ASSESSMENT

One particularly promising way of studying the interactions between climate and society is to trace the effects of a climatic event as they cascade through physical and social systems, and are disguised and modified by various sets of intervening factors. An example of this approach is offered by Warrich and Bowden (1981), tracking the impacts of drought occurrence in the U.S. Great Plains (Figure 6). These authors traced a variety of pathways that drought impacts could take, spanning a variety of spatial scales (from local to global) and a variety of systems (from agricultural to social). The cascade of effects of an anomalous climatic event work their way through a hierarchy of responses (e.g., climatic anomaly, crop yield, farm production, farm income, regional agricultural sector, regional economy, national economy, society). To understand and evaluate each level of response, we need to develop a hierarchy of models that can simulate these impacts. In particular, we can identify three sets of models: climatic changes, climate impacts on potential and actual yield, and the downstream economic and social effects of these (Figure 7). Scenarios using outputs from climate models (e.g., atmospheric general circulation models) or data from instrumental climatic records are used as inputs to agroclimatic models to predict potential or actual yield responses to climatic change. To trace the downstream effects of yield changes, outputs from the agroclimatic models are used as inputs to economic models (farm simulations, regional input-output models, etc.). It is then possible to consider what policies best mitigate certain impacts at specified points in the system. This research strategy has been adopted in a number of recent climate impact assessments, the results of which are summarized in the next section.

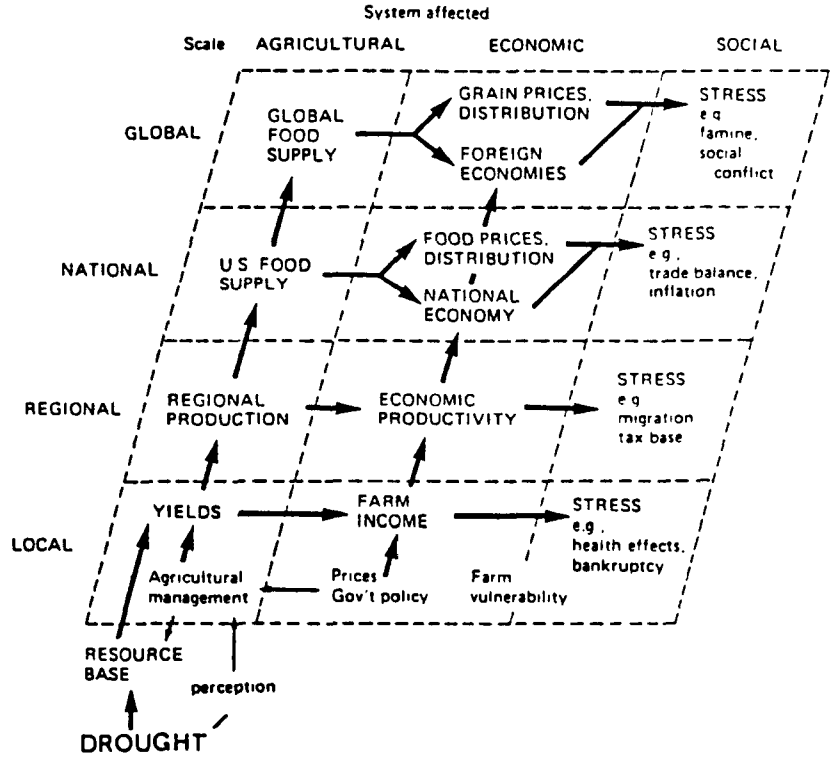


Figure 6. The Hypothetical Pathways of Drought Impacts on Society (Warrick and Bowden 1981).

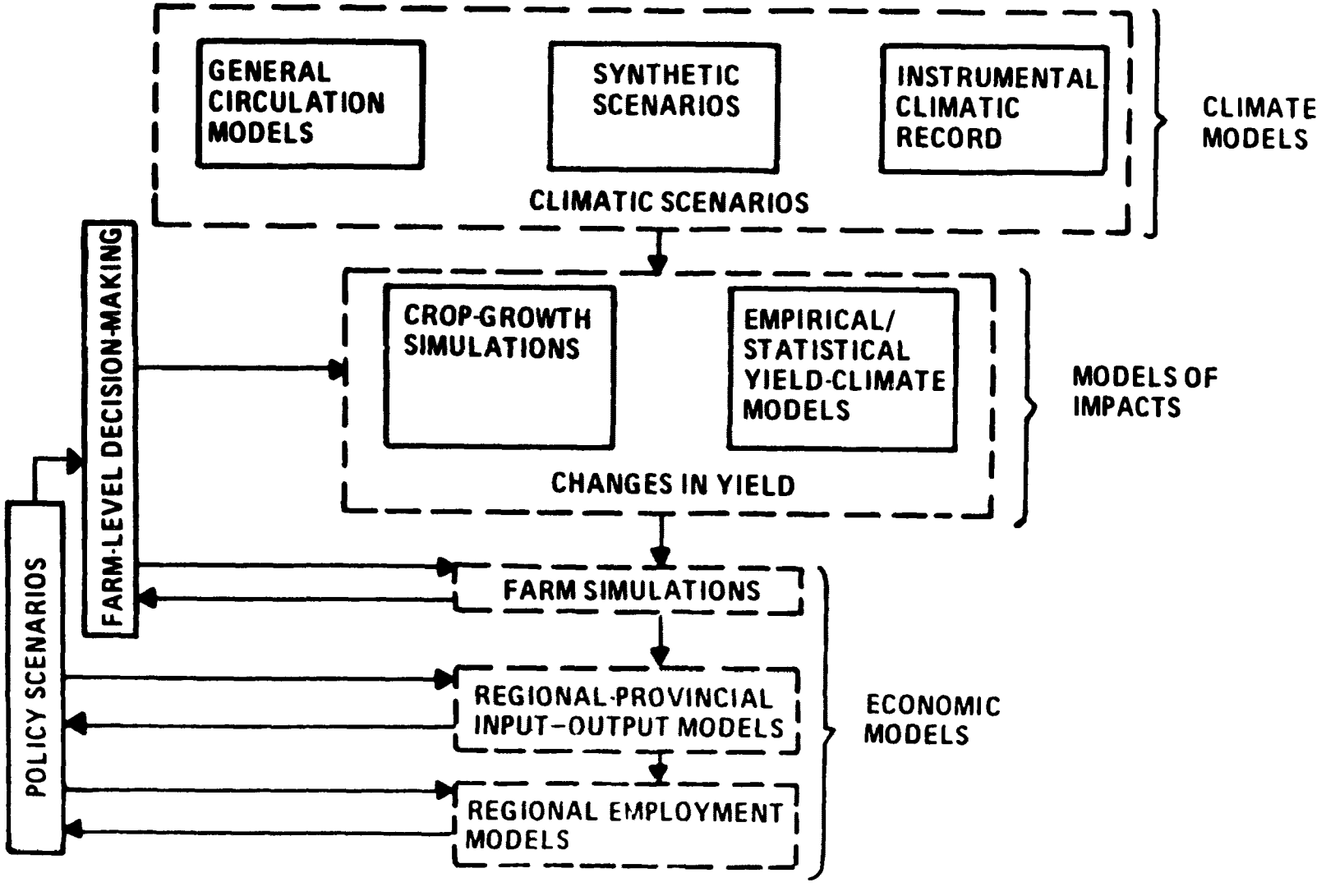


Figure 7. A hierarchy of models for the assessment of climate impacts and the evaluation of policy responses in the IIASA/UNEP Climate Impacts Project (Parry et al. 1986).

Recent Assessments 1: Effects on Crop Yields

In this section we draw heavily from a recent review by Warrich, Gifford, and Parry (1986) who have summarized results from a number of studies. We reduce here part of their summary, updated to include recent results from the Soviet Union (Figure 8). In essence, Warrich's conclusion is that, despite the diversity of modeling methods and scenarios adopted in these different studies, there is a remarkable degree of unanimity regarding the expected direction of effects of climatic changes on crop yields. Warming appears detrimental to cereals in the core wheat-growing areas of North America and Europe. With no change in precipitation (or radiation), slight warming (+1°C) might decrease average yields by about 1 to 9 percent while a 2°C increase might reduce average yields by about 3 to 17 percent. To place this in perspective Warrick notes that a 10 percent decrease in wheat and maize yields in North America is equivalent to about 20.5 million metric tons, or 10 percent of global trade in cereals. Reduced precipitation also tends to decrease yields, implying that both higher precipitation and temperature could have offsetting effects on yields, as reflected in the negative slope to the plots in Figure 8. To these conclusions we add first, that quite different effects on the same crop may occur in different regions (note the differences for the same wheat cultivar in Perm, 58°N latitude, and Volgograd, 48°N latitude) and that different cultivars may respond quite differently. We shall see later that these variations can be important in suggesting the kinds of technological adjustments that may be most appropriate for responding to a given climate change.

If, for the present, we ignore the adjustment in agriculture, such as a switch of crops, that is likely to accompany or follow a long-term climate change, we may conclude that given the kind of changes in climate most likely to result from increased CO_2 and other greenhouse gases, particularly enhanced warming in higher latitudes, with summer dryness becoming more frequent over the continents at middle latitudes in the Northern Hemisphere, then decreases in yields on the order of 10 percent might occur in the core wheat production areas of North America and the USSR. We should emphasize, however, that such estimates are unrealistic in that they fail to acknowledge that adjustments in agriculture will occur.

Recent Assessments 2: Spatial Effects on Crop Location

One of the major adjustments most likely to occur is the spatial shift of cropping areas, which is somewhat akin to the shift of biomes that has occurred as a response to long-term climatic changes in the past (see section on forestry below). We can map this effect through a sequence of steps that has been summarized by Parry (1985) as follows:

- Identification of the climatic variables that constrain crop growth in the region and limit its spatial extent
- Identification of critical levels of those that limit the spatial extent of the crop
- Characterization of climatic changes as changes of the critical levels
- Mapping these as a shift of extent of the crop.

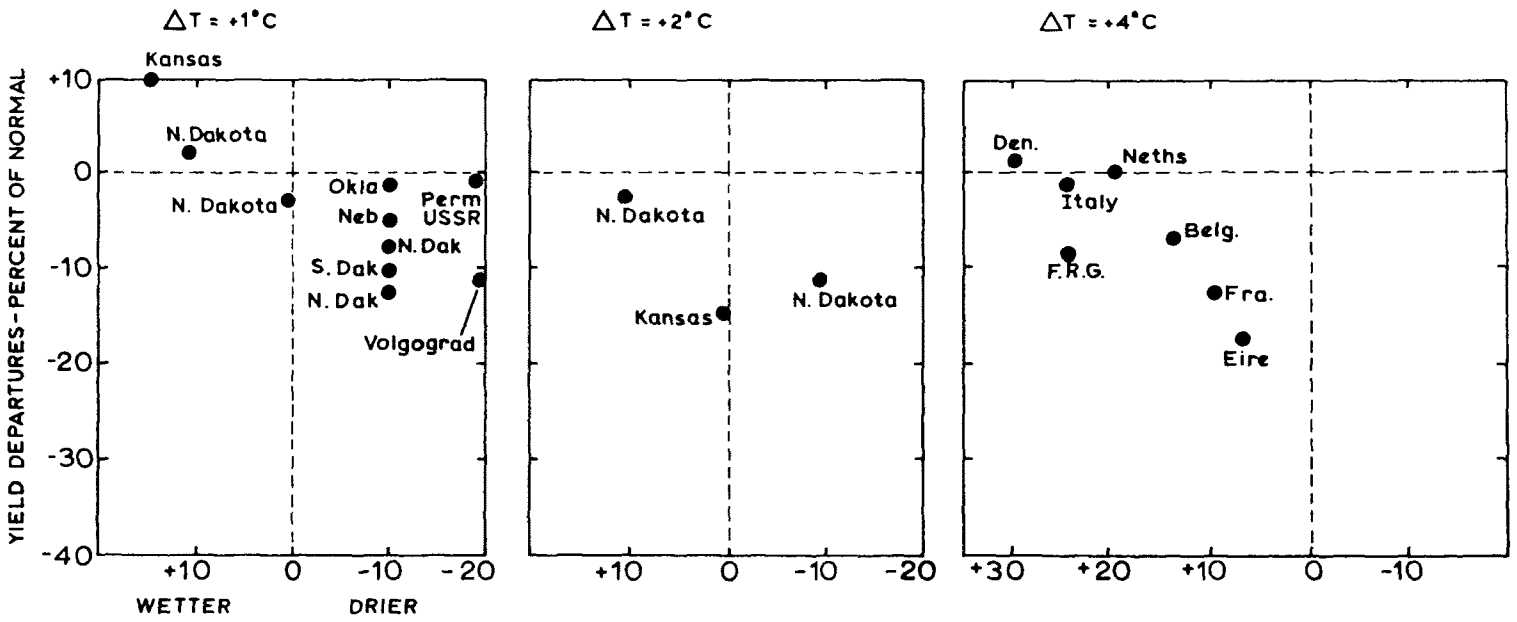


Figure 8. Estimates of wheat yield impacts for various scenarios of temperature and precipitation change (Warrick, 1986).

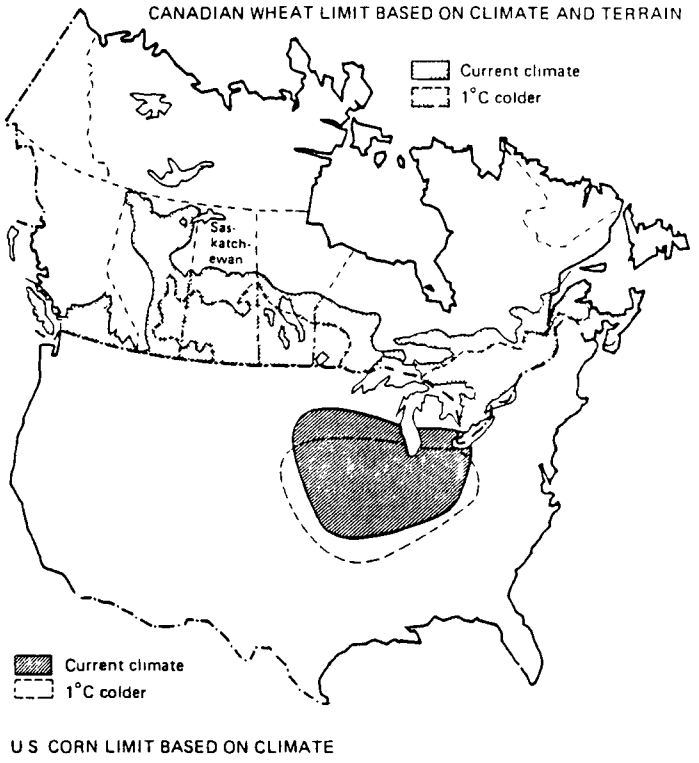


Figure 9. Estimated shift of the Canadian Spring Wheat Belt and the U.S. Corn Belt in response to a 1 degree reduction in annual temperature (after Williams and Oakes 1978; Newman 1980).

This approach has been used to estimate the effects of climate change on wheat- and maize-growing areas in North America. In Canada the isopleth bounding the wheat-maturing zone is based on photothermal time scale equations which consider the date of first fall freeze, growing season temperature, and radiation conditions (Williams and Oakes 1978). For the U.S. corn belt the limits have been expressed in terms of minimum frost-free period for maturity, minimum and maximum thermal requirements, and moisture requirements. Both crop zones are shown as shaded areas in Figure 9. In this example, an arbitrary decrease of 1°C has been used to perturb the crop zones. In Canada the area of spring wheat is reduced by about one-third. In the corn belt, a 1°C cooling with no change in precipitation would shift the belt in a south-westerly direction by about 175 kilometers since moisture stress would be reduced at the drier SW margin while the growing season would be reduced at the cool NW margin. A logical development of this approach is to consider the shift of wheat-growing regions for climatic scenarios predicted by general circulation models for doubled concentrations of CO_2 experiments. The model projects a great extension of the winter wheat belt into Canada, a switch from hard to soft wheat in the Pacific Northwest due to increased precipitation, and an expansion of areas in fall-sown spring wheat in the southern latitudes due to higher winter temperatures. In Mexico, wheat-growing regions would remain the same but greater high-temperature stress may occur (Figure 10).

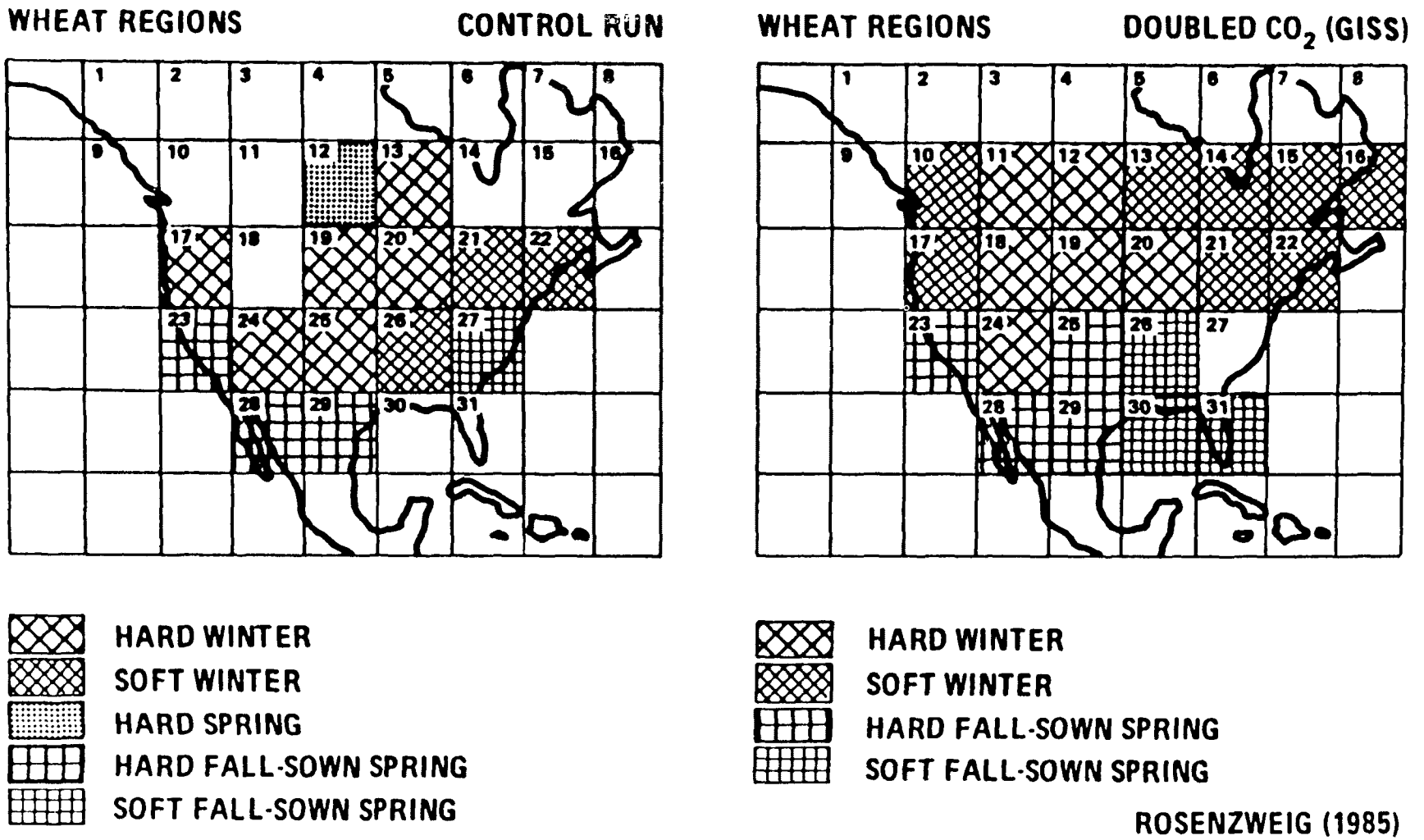


Figure 10. Simulated N. American wheat-growing areas using a) the GISS GCM control run and b) the GISS GCM doubled CO_2 run (Rosenzweig 1985).

Recent Assessments 3: Potential Effects on the Regional Agricultural Economy

Hierarchies of linked models, similar to those discussed above, have been used to assess the potential effects of climatic changes on the regional economy. In the International Institute for Applied Systems Analysis/UNEP project (Parry 1986) climatic scenarios using outputs from climate models (e.g., model experiments for doubled CO_2 climate) provide inputs to agroclimatic models to estimate potential or actual yield responses to climatic change. Output from the agroclimatic models provide inputs to the economic models (e.g., farm simulations, regional input-output models, etc.). While each set of models attempts to simulate a limited number of feedback effects within its own subsystem, the form of analysis is essentially sequential, allowing estimates to be made of a series of effects based on an assumed and essentially static set of agronomic and economic responses. We may call calculations "impact experiments"; they record the impacts that would occur if there were no changes in the farming system. However, as we have seen, farming systems have been remarkably adaptive to climatic changes in the past and we can reasonably expect them to be in the future. The major task we face is to make the adaptations in an optimal manner, that is, with the minimum of social and economic cost. It is possible to evaluate the various options that are available for either mitigating the negative effects or exploiting the positive ones by altering some of the assumptions in our agroclimatic and economic models, for example, by experimenting with a switch to a different crop, different amounts of fertilizer, or different amounts of irrigation. For each set of these "adjustment experiments" we can generate a new set of impact estimates that can be compared with the initial impact estimates (on the unadjusted system), and thus begin to identify the more appropriate types of adjustment to various types of climatic change.

In the summary that follows we outline results selected from a wide range of experiments for both impacts and adjustments. Only a few are presented here. These are drawn from studies conducted in Canada, the Soviet Union and Japan. Other studies in the IIASA/UNEP project were conducted in Iceland, Finland, Ecuador, Brazil, Kenya, India, and Australia (Parry 1986). In each case study region a series of three or four impact experiments were conducted along the lines outlined above and in a broadly compatible manner. These were then followed by a series of adjustment experiments to evaluate the appropriateness of various responses. In the example summarized here the emphasis was on the potential effects of climatic changes due to increased atmospheric CO_2. Scenarios of these changes were based on outputs from the doubled-CO_2 experiment for the GISS GCM. To compare these effects with the effects of short-term climatic variations, the results were compared with those for an extreme decade and extreme year scenario. Because different crop-weather models require different data (ten-day, monthly, annual, etc.), this array of scenarios varied somewhat between the case studies. The Soviet study, for example, includes synthetic scenarios that vary temperature and precipitation by arbitrary increments. In general, however, the results permit comparison of the potential effects of a doubled CO_2 climate both between different regions and between the effects of a long-term climate change and short-term climatic variability. The results are, of course, not predictions. A high level of uncertainty is attached both to model predictions of regional climatic change and to the estimations of their effects on agriculture.

Regional Variations in Effects on Crop Yields. As indicated above, the higher temperatures that may be expected to prevail under conditions of increased atmospheric CO_2 tend to favor higher yields of cereal crops now grown in regions where temperature limits the growing season. In the central European region of the Soviet Union, for example, wheat yields under the doubled CO_2 climate projected by GISS increase by about one third (Table 1). If we assume that these warmer conditions do not create problems of water supply and that, for example, Japanese rice production will remain fully irrigated, we may expect average rice yields in central Japan (To Kohu) to increase by perhaps 5 percent (Table 2). However, where cereal production is already drought-prone, increased rates of evapotranspiration may well place a brake on output. Simulations of wheat yield in Saskatchewan point to quite severe early-summer moisture stress on ground spring-sown wheat plants with consequent yield reductions of between one-fifth and a third, depending on soil type (Table 3). As we discuss below, one way of mitigating these negative effects is to switch from spring- to winter-sown wheat. However, the regional pattern of crop yield responses will probably be extremely varied for a number of reasons.

- Spatial Complexity of the Climate Change. This is not simply the result of the varying degrees of absolute change in temperature, precipitation, cloudiness, etc., and other factors that could be expected to occur in different places, but also stems from the ratio of this change to the existing climate. Thus, while effective temperature sums (ETS) in central Japan (To Kohu) increase by 27 percent in the GISS doubled CO_2 experiment, in the north at Hokkaido (where they are already one quarter lower than in the center) the increase is 37 percent. Thus much of the variation in yield response estimated for irrigated rice in Japan is a function of the geography of existing agroclimatic potential. This factor, as much as greater increases in temperature expected in Hokkaido, explains why average rice yields in Hokkaido increase by 8 percent and in To Kohu by 5 percent.

- Spatial Complexity Introduced by Non-climatic Factors. In the estimates presented above we have assumed the same terrain, soil, management, etc. When regional variations in these are introduced there can result quite localized variations in responses to climatic change. To illustrate, while spring wheat yields in Saskatchewan are reduced by one-fifth under the GISS projection for doubled CO_2 climate on brown soils, on black soils they are reduced by one-third. Overlaid on these variations are differences in infrastructure (farm size, etc.) and management (levels of fertilizer applications, pesticides, etc.). Even if we assume the same management for all farm sizes, the effects of similar yield changes on farm income vary according to farm size partly because of varying yield-income functions and partly because different sized farms are found on different soil types (Table 3).

Table 1. The effect of climatic variations on agricultural projection in USSR: Preliminary results of scenario experiments by the IIASA/UNEP Climate Impacts Project. Unless otherwise stated, estimates are relative to the 1951-80 climate and to yields simulated for that climate, with management and technology at c. 1980 levels. From Parry at al. 1986: see notes for individual authors.

	NORTHERN U.S.S.R.		BASELINE CLIMATE (1951-80) WITH 1980 TECHNOLOGY[1]		BASELINE CLIMATE WITH TECHNOLOGICAL TREND[2]		SCENARIOS: MODERATE WARMING[3]		SCENARIOS: GISS 2 X CO_2 EXPERIMENT $\Delta T \Delta P$[4]		SCENARIOS: GISS 2 X CO_2 EXPERIMENT WITH ADJUSTED TECHNOLOGY[5]	
PERM REGION	MEAN AIR TEMPERATURE		21	13.6°C	21	13.6°C	23	+1.0°C	24	+2.7°C	24	+2.7°C
PERM REGION	TOTAL PRECIPITATION		22	300 mm	22	300 mm	25	-20 mm to +20 mm	26	+50%	26	+50%
PERM REGION	SPRING WHEAT YIELDS						27,28	-1%	31	-3%	33	+16%
											32,33	+39%
							27,29	+3%	32	+17%	34	+26%
							27,30	+7%			32,34	+49%
CENTRAL REGIONAL EUROPEAN	MEAN AIR TEMPERATURE		35	6.6°C	35	6.6°C	37	+1.0°C	38	+1.5°C		
CENTRAL REGIONAL EUROPEAN	TOTAL PRECIPITATION		36	575 mm	36	575 mm	37	NO CHANGE	38	NO CHANGE		
CENTRAL REGIONAL EUROPEAN	WINTER WHEAT	YIELD[39]	43	20.3 q/ha	44	+3%	45	+33%	45	+30%		
		AREA[40]	46	150,000 ha	47	+0%	48	+29%	48	+26%		
		PRODUCTION[41]		3,045,000 q	51	+3%	48	+17%	48	+64%		
		COST[42]	52	15.0 r/q	53	+0%	48	-22%				
CENTRAL REGIONAL EUROPEAN	BARLEY	YIELD	43	17.0 q/ha	44	+4%	45	- 1%	45	- 4%		
		AREA	46	130,000 ha	47	+0%	48	-23%	48	-20%		
		PRODUCTION		2,210,000 q	51	+4	48	-23%	48	-23%		
		COST	52	13.0 r/q	53	+0%	48	+ 5%				

NOTES TO TABLE 1.

1. Unless otherwise stated (Iakimets, Pitovranov and Sirotenko).

2. Technology trend, 1980-2035, unless otherwise stated (Iakimets and Pitovranov).

3. Up to the year 2000 (Iakimets et al).

4. Goodard Institute for Space Studies (GISS) General Circulation model 2 x CO_2 experiment; output processed for impact experiments (Bach), unless otherwise stated.

5. GISS model climate, fertilizer, drainage or crop varieties adjusted.

21. May-September mean air temperature at Perm (station adjacent to Cherdyn), period undetermined.

22. May-September mean precipitation at Perm, period undetermined.

23. Arbitrary warming relative to 1951-80 baseline (May-September mean) (Sirotenko).

24. GISS model climate; May-September mean, interpolated from grid points to Cherdyn (Sirotenko).

25. Arbitrary variations in precipitation (May-September) (Sirotenko).

26. GISS model climate; calculated as 2 x CO_2 - 1 x CO_2 precipitation; interpolated from grid point data (Sirotenko).

27. Simulated yield relative to modeled 1951-80 mean yield (Sirotenko).

28. Precipitation 29 mm below baseline (Sirotenko).

29. Baseline precipitation (Sirotenko).

30. Precipitation 20 mm above baseline (Sirotenko).

31. Present crop variety and farming efficiency (Sirotenko).

32. Simulation incorporating direct effects of CO_2 on plant photosynthesis and water use (Sirotenko).

33. New middle-maturing variety requiring an extra 50 GDD temperature during the growing season (Sirotenko).

34. New late-maturing variety requiring 100 GDD higher temperature during the growing season (Sirotenko).

35. Annual mean air temperature at Moscow (assumed representative of the Central Region), period undetermined.

36. Annual mean precipitation at Moscow, period undetermined.

37. Arbitrary temperature change relative to baseline (annual mean); precipitation unchanged, assumed to occur in 1995 (Kiselev).

38. As in Note 37, this is not the GISS scenario (Kiselev).

39. Based on 1970-80 technology trend (Kiselev).

40. Area of crop required to minimize total expenditure (Kiselev).

41. The product of area and crop yield (Kiselev).

42. Expenditure per hectare and resource supply function (Kiselev).

43. Trend yield for 1980, quintals per hectare (Kiselev).

44. Trend yield extrapolated to 1995, relative to 1980 trend yield (Kiselev).

45. Estimates relative to 1980 trend yield using crop production simulation model (Kiselev)

46. Cropped area in 1980 (Kiselev).

47. Cropped area under improved technology, assumed the same as in 1980 (Kiselev).

48. Optimization model for minimizing expenditure: values relative to 1980 (Kiselev).

49. Area of perennial grassland for hay production fixed at 1980 value (Kiselev).

50. Mix of crops chosen primarily to meet human demand for vegetable products (Kiselev).

51. Trend production (matching yield trend) (Kiselev).

52. Cost based on trend data (rouble/quintal), 1980 values (Kiselev).

53. Costs assumed the same, under improved technology, as in 1980 (Kiselev).

Table 2. The effect of climatic variations on agricultural production in Japan: Preliminary results of scenario experiments by the IIASA/UNEP Climate Impacts Project. Unless otherwise stated, estimates are relative to the 1951-80 climate and to yields simulated for that climate, with managment and technology at c. 1980 levels. From Parry et al. 1986: see notes for individual authors.

			SCENARIOS				
JAPAN		BASELINE 1951-80[1]	COOL SUMMER YEAR[2]	UNSTABLE DECADE[3]	STABLE DECADE[4]	"GOOD" YEAR[5]	GISS 2 x CO_2 EXPERIMENT ΔT[6]
HOKKAIDO	MEAN AIR TEMPERATURE	[7] 20.6°C	[7] -1.6°C	[8] +0.0°C	[8] +0.0°C	[7] +2.5°C	[9] +3.5°C
	EFFECTIVE TEMPERATURE SUM	[10] 3000 GDD	[10] -13%	[10] +0%	[10] +0%	[10] +27%	[10] +37%
	RICE CULTIVATION LIMIT	[11] 250 m	[12] -222 m			[12] +429 m	[12] +587 m
	RICE YIELD INDEX	100	[13] -38%			[13] +19%	[13] +8%
TOHOKU	MEAN AIR TEMPERATURE	[7] 22.8°C	[7] -2.6°C			[7] +2.3°C	[9] +3.2°C
	EFFECTIVE TEMPERATURE SUM	[10] 3700 GDD	[10] -22%			[10] +20%	[10] +27%
	RICE CULTIVATION LIMIT	[11] 350 m	[28] -381 m			[28] +397 m	
	RICE YIELD INDEX	100	[13] -46%			[13] +11%	[13] +5%
WHOLE JAPAN	NATIONAL RICE SUPPLY	[25] 12.25 M tons	[28] -21%			[26] +1%	
	NATIONAL RICE STOCK	[25] 12 M tons					[25] 20 M tons

NOTES TO TABLE 2

1. Unless otherwise stated.

2. 1980, unless otherwise stated.

3. 1974-83, unless otherwise stated.

4. 1957-66, unless otherwise stated.

5. 1978, unless otherwise stated.

6. Goddard Institute for Space Studies (GISS) General Circulation Model 2 x CO_2 experiment; output processed for impact experiments (Bach). Air temperature change only; precipitation change not considered important for irrigated rice crops in impact experiments.

7. District average; July-August air temperature (T. Uchijima).

8. District average; July-August air temperature (Horie).

9. Calculated as 2 x CO_2 - 1 x CO_2 temperature; spatial average (T. Uchijima).

10. Effective temperature sum (ETS) above 10°C base; values based on relationship between July-August air temperature and ETS over all Japan (150 station) (Uchijima and Seino).

11. Present altitudinal limit (meters) (T. Uchijima).

12. Using temperature lapse rate and ETS threshold for rice cultivation of 2600 GDD (above 10°C base). Values relate to a baseline temperature of 20.4°C (T. Uchijima).

13. Rice yield regression index developed for 1888-1983 detrended yields. Values relative to baseline index value of 100 (T. Uchijima).

25. Integrated Economic and Climatic Model; Simulation period 1966-82 (Tsujii).

26. Approximate value relative to 1966-82 baseline (Tsujii).

27. July-August temperature change of 3.4°C (Tsujii).

28. Using temperature lapse rate and ETS threshold for rice cultivation of 2600 GDD (above 10°C base). Values relate to a baseline temperature of 22.5°C (T. Uchijima).

Table 3. The effect of climatic variations on agricultural production in Canada; Preliminary results of scenario experiments by the IIASA/UNEP Climate Impacts Project. Unless otherwise stated, estimates are relative to the 1951-80 climate and to yields simulated for that climate, with manageemnt and technology at c. 1980 levels. From Parry et al. 1986; see notes for individual authors.

		SCENARIOS			
CANADA (SOUTHERN SASKATCHEWAN)[1]	BASELINE 1951-80[2]	DRY YEAR (1961)	DRY PERIOD (1933-37)[3]	GISS 2 x CO_2 EXPERIMENT $\Delta T \Delta P$[4]	GISS 2 x CO_2 EXPERIMENT ΔT[5]
MEAN AIR TEMPERATURE	[6] 14.5° to 16.6°C	+0.3°C to +3.5°C	-1.3°C to +2.3°C	[7] +3.4°C	[7] +3.4°C
TOTAL PRECIPITATION	[6] 175 to 250 mm	-45 mm to -12 mm	-62 mm to -39 mm	[8] +18%	NO CHANGE
TOTAL PROVINCIAL WHEAT PRODUCTION	[22] 175 M bu	[23] -76%	[23] -44%	[23] -25%	[23] -37%
TOTAL PROVINCIAL FARM INCOME	[25] $2290 M	[21] -78%	[21] -38%	[21] -26%	[21] -39%
EMPLOYMENT AGRICULTURAL SECTOR	[22] 88,000 my	[26] -9.1%	[26] -4.4%	[26] -3.0%	[26] -4.6%
EMPLOYMENT OTHER SECTIONS	[22] 335,000 my	[26] -5.1%	[26] -2.5%	[26] -1.7%	[26] -2.6%
TOTAL PROVINCIAL EMPLOYMENT	[22] 423,000 my	[26] -5.9%	[26] -2.9%	[26] -1.9%	[26] -3.0%
PROVINCIAL HOUSEHOLD PURCHASING POWER (GDP)	[27] $6260 M	[28] -38%	[28] -18%	[28] -12%	[28] -19%

NOTES TO TABLE 3

1. Calculations for a northern station, Uranium City, are footnoted where appropriate.

2. Unless otherwise noted.

3. Unless otherwise noted.

4. Goddard Institute for Space Studies (GISS) General Circulation Model 2 x CO_2 experiment; output processed for impact experiments (Bach). Air temperature and precipitation changes included in scenario.

5. GISS model outputs: air temperature changes only. Precipitation fixed at 1951-80 baseline.

6. May-August: all crop districts: precipitation values rounded to nearest 5 mm (Stewart)
   Uranium City values: 12.8°C, 149 mm.

7. Calculated as 2 x CO_2 - 1 x CO_2 temperature; spatial average (Stewart).

21. Estimates from farm level simulation models (Fautley).

22. 1980 value (Fautley).

23. Aggregated for all crop districts based on yield simulations (Stewart).

24. Income aggregated by farm size, whole province; 1980 values; all cereals (Fautley).

25. Aggregated for all farms, whole province; 1980 values; all cereals (Fautley).

26. Employment model (Fautley).

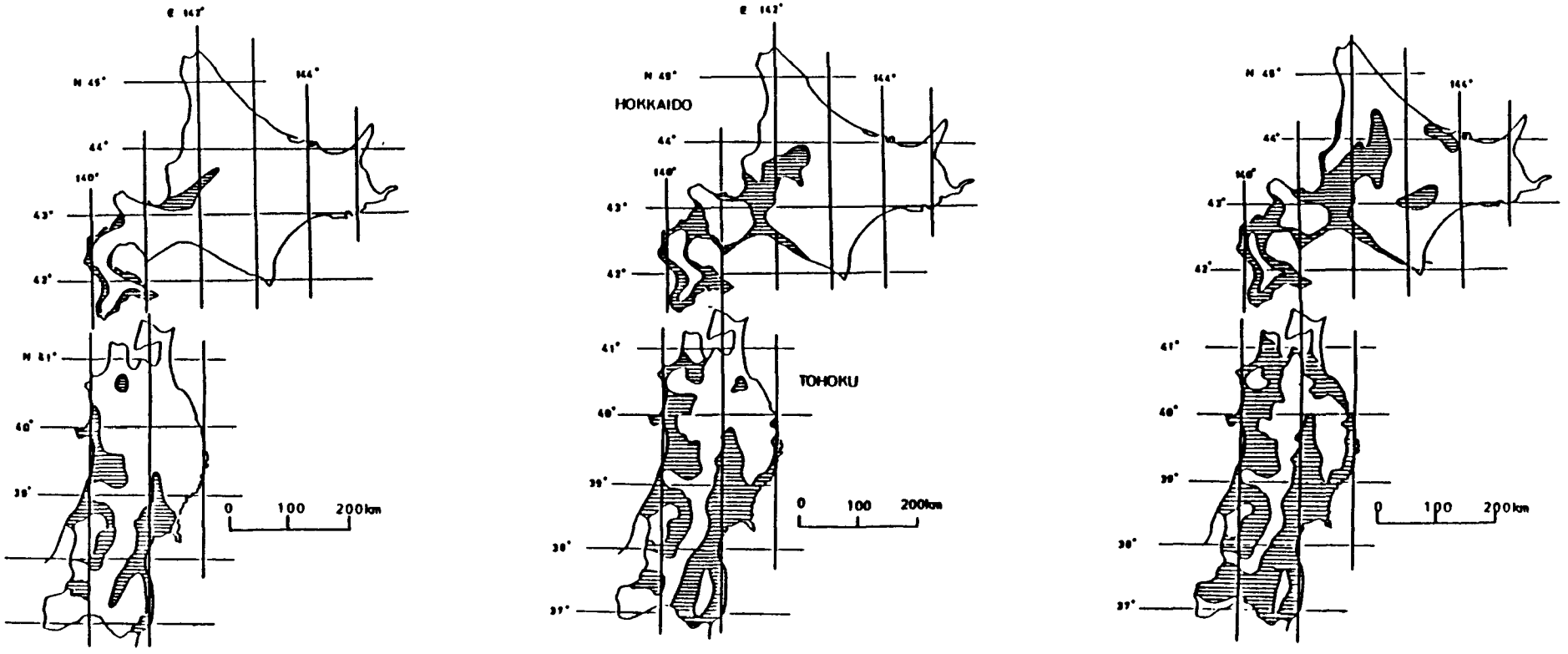
27. 1980 data; whole province (Fautley).

28. Input-out model (Fautley).

- Differential Crop Responses. Because different crops have different growing requirements, they frequently respond quite differently to changes in their environment. In the central-European part of the Soviet Union, for example, a moderate warming would increase winter wheat yields (which are at present limited by a short, relatively cool growing season in the region) but decrease barley yields (since spring-sown barley is suited to the cool conditions but is susceptible to the early summer moisture stress that might accompany increased temperatures). Under a warming experiment ($\Delta T = +1.5^{0}C$) winter wheat yields in this region increased by 30 percent and barley yields decreased by 4 percent (Table 1). As might be expected, cool temperate crops such as oats and potatoes also decrease, while corn (maize) increases.

- Resultant Changes in Crops' Potential. Two consequences flow from the geographic complexity described above: there are spatial shifts of crop potential and spatial shifts of comparative advantage. Areas that, under present climatic conditions, are judged to be most suited to a given crop, combination of crops, or a specified level of management will change location. This means that a change will occur in the range of crops that can be profitably grown at a particular place, as a result of the shift of the physiological limits for growth of different crops. For example, we might expect that under a warmer climate both winter and spring wheat will expand northward, assuming that terrain and soils permit. This is well-illustrated in Hokkaido, where the limits of the "safely cultivable" area for irrigated rice (defined as a return period of critically low growing season temperatures that can cause failure of the rice crop) fluctuate quite markedly between warm and cool periods and could be expected to expand under a climatic warming induced by increased atmospheric CO_2 or other greenhouse gases (Figure 11).

- Spatial Shifts of Comparative Advantage. More important are the changes in area under different crops resulting from differential changes in yield that, in turn, result in changes either in their relative profitability at a particular place or in the comparative advantage that one crop may hold over another. For example, under a market system, it is probable that, if other factors remain unchanged, crops that exhibit a substantial decrease in yield would be displaced by those that show an increase in yield. An important assumption here is that alternative areas are available for production of this displaced crop. The relative availability of potential production areas would affect their comparative advantage. If alternative areas were not available, the crop might not be displaced and there would be no radical change in the pattern of land use. The operation of these forces of supply and demand in determining how much change occurs in the pattern of land use can be more clearly seen in a centrally planned economy such as that of the Soviet Union. To illustrate this point Table 1 includes results from experiments with an optimization model that allocates land to various crops to minimize expenditure on inputs (e.g., fertilizers and machinery) while meeting certain regional production targets. Under the +1.5°C experiment this approach increases the allocation of land to winter wheat by 26 percent while reducing that under barley by 20 percent reflecting the



a) COOL DECADE

b) NORMAL

c) WARM DECADE

Figure 11. Shift of safely cultivable area for irrigated rice in Hokkaido, N. Japan (Uchijima in Parry, et al. 1986).

fact the wheat yields increased by 30 percent and barley yields fell by 4 percent.

- Inter-regional Differences in Crop Yield Sensitivity. The picture is further complicated by the fact that the same crop grown in different regions will respond differently to the same change in climate. In northern Finland under the GISS scenario, for example, barley would relish a higher ETS without moisture shortage, whereas in southern Finland yields could actually decrease because of early summer moisture stress (for details see Parry 1986). Comparable sensitivity analyses of spring wheat yields in the northern and southern parts of the European USSR indicate similarly contrasting responses. In Perm (west of the Ural Mountains) yields increase with increasing temperature, while in Volgograd (some 1,000 km further south) they decrease (Table 1). These differing regional responses will, in turn, affect the pattern of comparative advantage in cropping and thus influence the shift of cropping patterns that may result from changes in climate.

- Effects on Crop Responses to Management. One of the difficulties of estimating effects of climatic change on agriculture is that the sensitivity of yield to inputs, such as fertilizers and pesticides, also varies with climate. Generally speaking, the more ideal the climatic conditions are for plant growth, the greater the plant response to fertilzer applications, which means that adjusting levels of fertilization can be an effective means of stabilizing yield variability resulting from short-term climatic changes.

- Effects on Variability of Production. Even if we disregard those changes in interannual variability of temperature and rainfall that may occur as part of a transition to a warmer climate and assume that climatic variability remains unchanged, the effect of a change in mean climate on mean yield can be different from its effect on the above- or below-average yields. Figure 12, for example, shows that in southern Finland quite different increases occur in the 5-percent, mean, and 95-percent spring wheat yields simulated for the recent warm period 1966-73, and that similar (though perhaps less pronounced) differences are likely to occur with different wheat varieties in a the doubled CO_2 climate projected by GISS.

Recent Assessments 4: Downstream Economic Effects

From experiments with farm simulation models and input-ouput models, we can estimate the effects of climatic changes, via crop yields, on farm incomes, employment, and levels of economic activity in nonagricultural sectors. The critical parameters here are the relationships between yield and farm income, farm income and on-farm employment, and farm income and expenditures by farmers of nonagricultural goods. These relationships are described by regression equations that pertain to a particular data set (for example, the models for Saskatchewan are based upon data for 1974 and 1980). They allow an estimation of the effects of a specific climatic event, such as an extreme dry year or dry decade, if that event were to occur now. But these background factors are constantly changing and, indeed, would almost certainly change in response to a longer term transient change in climate resulting from, for example, increases in atmospheric CO_2 or other greenhouse gases.

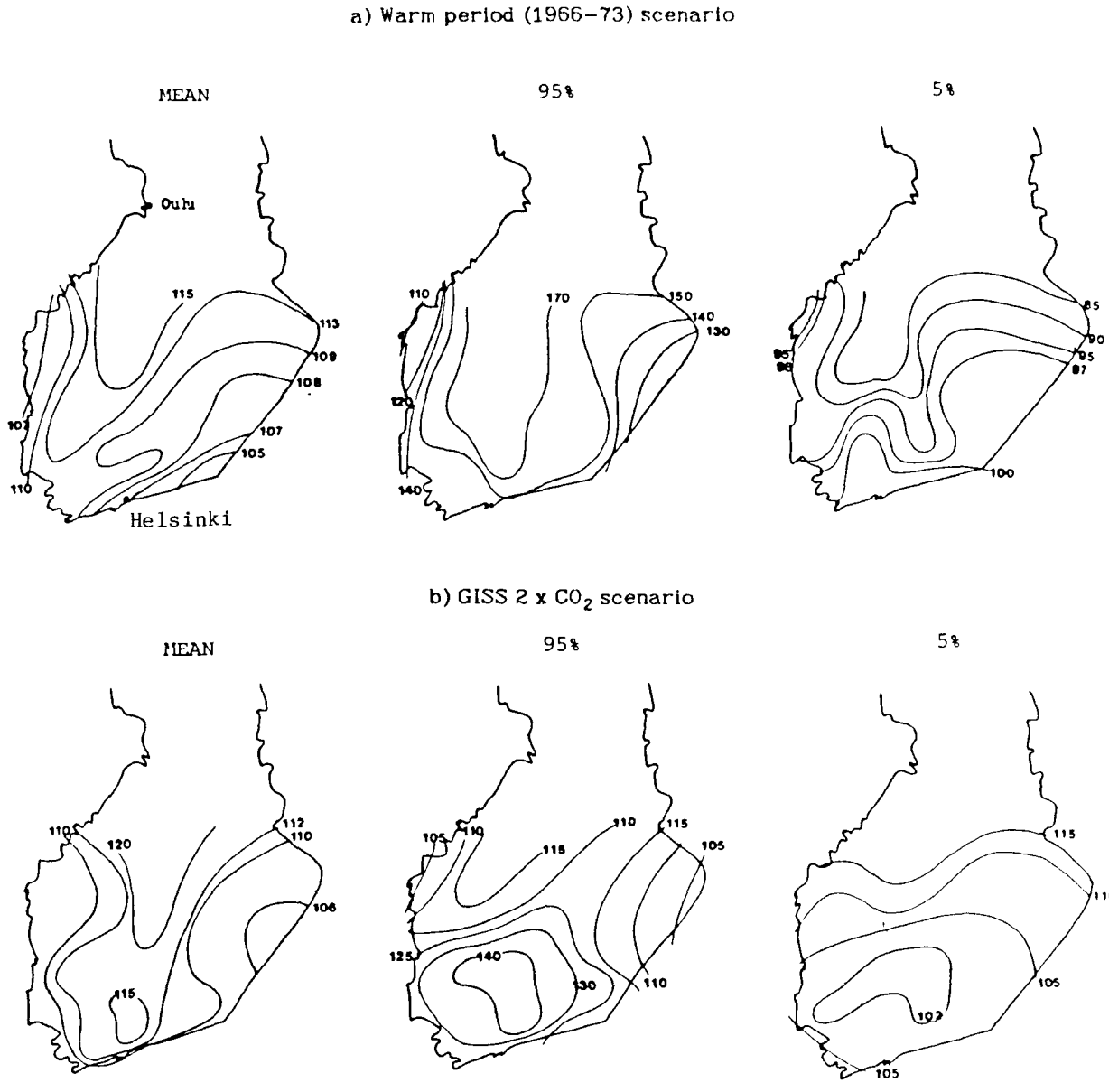


Figure 12. Effect of climate on mean, lowest (95 percentile) and highest (5 percentile) spring wheat yields in Finland a) for warm period 1974-82, with present-day variety; b) for GISS "2 x CO_2" climate with adapted variety having thermal requirement 120 GDD greater than present varieties. Isolines indicate percentage of yield simulated for the period 1959-83. From O. Rantanen, in Parry et al. 1986.

With these caveats in mind, we report that experiments in Saskatchewan indicate that under the changes in temperature and precipitation indicated by the GISS projections, total provincial farm income decreases by 26 percent, on-farm employment by 3 percent, and provincial gross domestic product by 12 percent. Considerable margins of error embrace these estimates. For details, see Fautley in Parry (1986). In this experiment the change in climate is treated as a sudden, step-like event in which no adjustment is allowed for changes in technology, management, prices, harvested area, etc. In reality we can be sure that these would change substantially between now and the time at which levels of atmospheric CO_2 are doubled. Current estimates for the CO_2 doubling time lie between 2050 and 2100 (Bolin et al. 1986).

Because of the uncertainties surrounding future changes in prices, management, and technology, the results from these experiments present an extremely unreal picture of the effect of long-term climatic changes. They do, however, provide a means of testing a number of adjustments to climate change by comparing the results of the adjusted experiments with those of the initial, unadjusted ones. The analysis can thus take on an interactive form which more closely resembles the dynamics of the real world. These adjustments are discussed in the following section.

Recent Assessments 5: Some Technological Responses to Climatic Changes

In this section we refer only to adjustments that could be put in place now, since this enables us to parameterize and input them to the linked models. Vague assumptions about future changes in technology, demand, and prices are much less easy to specify. The adjustments are of four types: crop variety, soil management, land allocation, and purchases to supplement production.

Changes in Crop Variety. Changes in crop variety can be made to respond to climatic changes. Such problems include changing from spring to winter varieties, changing to varieties with higher thermal requirements, and changing to varieties that give less varied yields.

- Change from Spring to Winter Varieties. Our investigations in Canada, Finland, and the northern USSR indicated that spring-sown crops (e.g., wheat, barley and oats) experienced reduced yields under the GISS projections of future climate because the increased frequency of moisture stress early in the growing period (see Tables 1 and 3). A switch to winter wheat or, in some areas, winter rye might reduce the effects of high evaporotranspiration in the early summer a well as taking advantage of the longer potential growing season (assuming that snow cover remained sufficient to protect the crop against winter kill). In Saskatchewan, the Prairie Farm Rehabilitation Administration (PRFA) has experimented by switching 5 percent of the cropped area from spring wheat to winter wheat to assess the effect on average yield and yield security. The initial work has focused only on dark brown soils and for a single extreme year (the 1961-type drought). This indicates that while overall wheat production would be less than at present in a normal year as a result of this change, it would be greater in a drought year. The next step is to evaluate the effects over five or ten years of variable weather to see which mix of varieties offers the longest aggregate production or, alternatively,

the most stable income over a given period. The PFRA could then recommend various planting strategies for various farming goals.

- Change to Varieties with Higher Thermal Requirements. A logical way of exploiting longer and warmer growing seasons at high latitudes is to use later maturing varieties with higher thermal requirements. In some cases the yields of present-day varieties such as spring wheat in northern USSR and early-maturing rice in Northern Japan tend to be reduced under the GISS climate projections for doubled CO_2 (see Table 2). However, spring wheat varieties with thermal requirements 50 to 100 GDD greater than present-day varieties exhibit increased yields. Allowing both for the direct effects of atmospheric CO_2 on plant photosynthesis and water use and the change in varieties, spring wheat yields in the Perm regions are a third to a half greater than at present (Table 1). In Hokkaido, late-maturing varieties of rice (at present grown in central not northern, Japan) gave yields about 30 percent greater under the GISS scenario than the present early variety grown in Hokkaido.

- Change to Varieties Giving Less Variable Yields. We know little about what changes could occur in the interannual variability of temperature and precipitation. But, even if we assume the same degree of variability under an altered climate, the effects on crop yields would be significant; it is possible to test a number of varieties for stability of yield. Figure 13 illustrates graphically the effects of the climate projected by GISS on two different varieties (for further details see T. Horie in Parry 1986).

Changes in Fertilizing and Drainage. Also can be made to respond to climatic change.

- Altered Fertilizer Applications. The IIASA/UNEP project includes two types of fertilizer experiments. The first increases levels of fertilizer application to optimize yields under the climate for doubled CO_2 projected by GISS. The second varies applications to maintain, for example, 1980 production levels. Variable applications of fertilizer to stabilize yields by offsetting the effects of anomalously cool or warm summers are at present being tested for feasibility by the Icelandic government (for details, see Iakimets et al. and Bergthorsoon et al. in Parry 1986).

- Improvements in Soil Drainage. Increased precipitation predicted in the GISS experiment for doubled CO_2 might be expected to cause increased soil erosion, which might offset the beneficial effects of a warmer climate and technological improvements. It should be noted that precipitation may well be considerably exaggerated by the GISS model. Improvements in soil drainage are therefore tested in the IIASA study of the Leningrad region of northern USSR, which indicated slightly reduced yields, presumably a result of the leaching of soil nutrients. This effect would have to be weighed against reduced erosion and more efficient disposal of nitrate pollutants in the regions to fully assess the consequence of such a measure (see Iakimets et al. in Parry 1986).

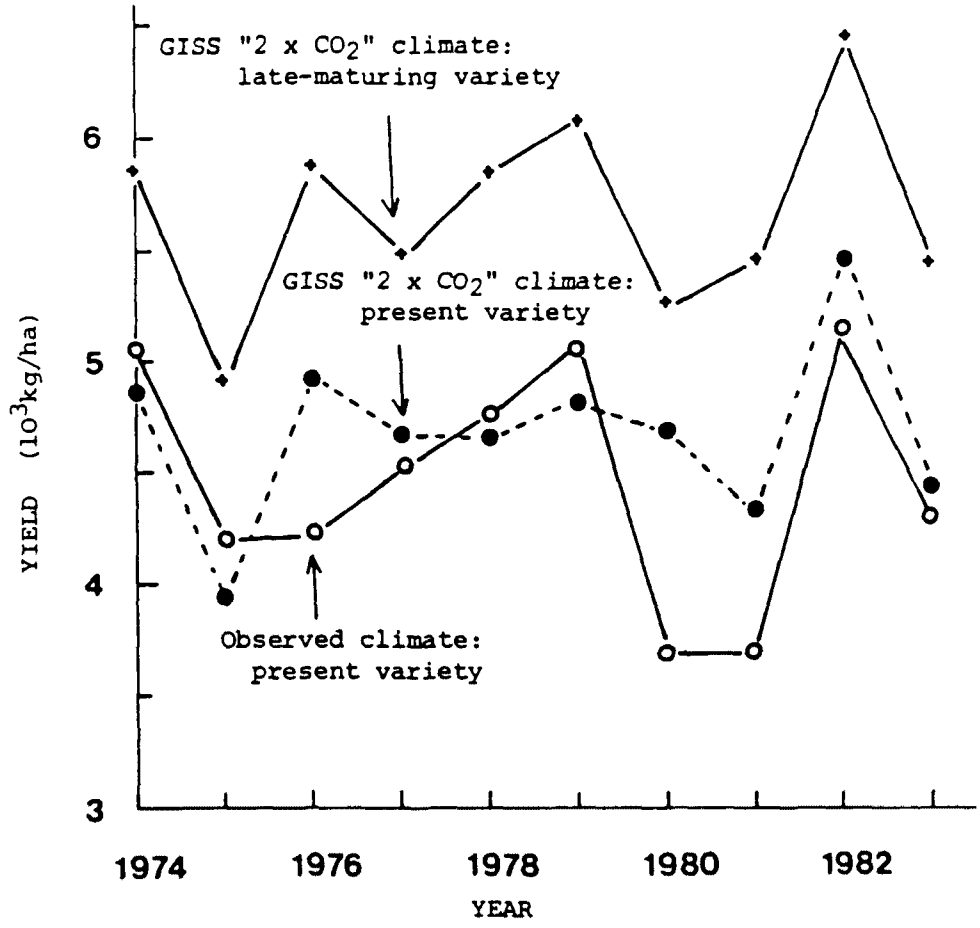


Figure 13. Simulated rice yield under present (observed) and GISS "2 x CO_2" climate applied to 1974-83 in Hokkaido, N. Japan. Responses to the doubled CO_2 climate of two varieties of rice are shown. From T. Horie in Parry et al. 1986.

Changes in Land Allocation. Finally, land allocation can be changed to respond to the effects of climatic change.

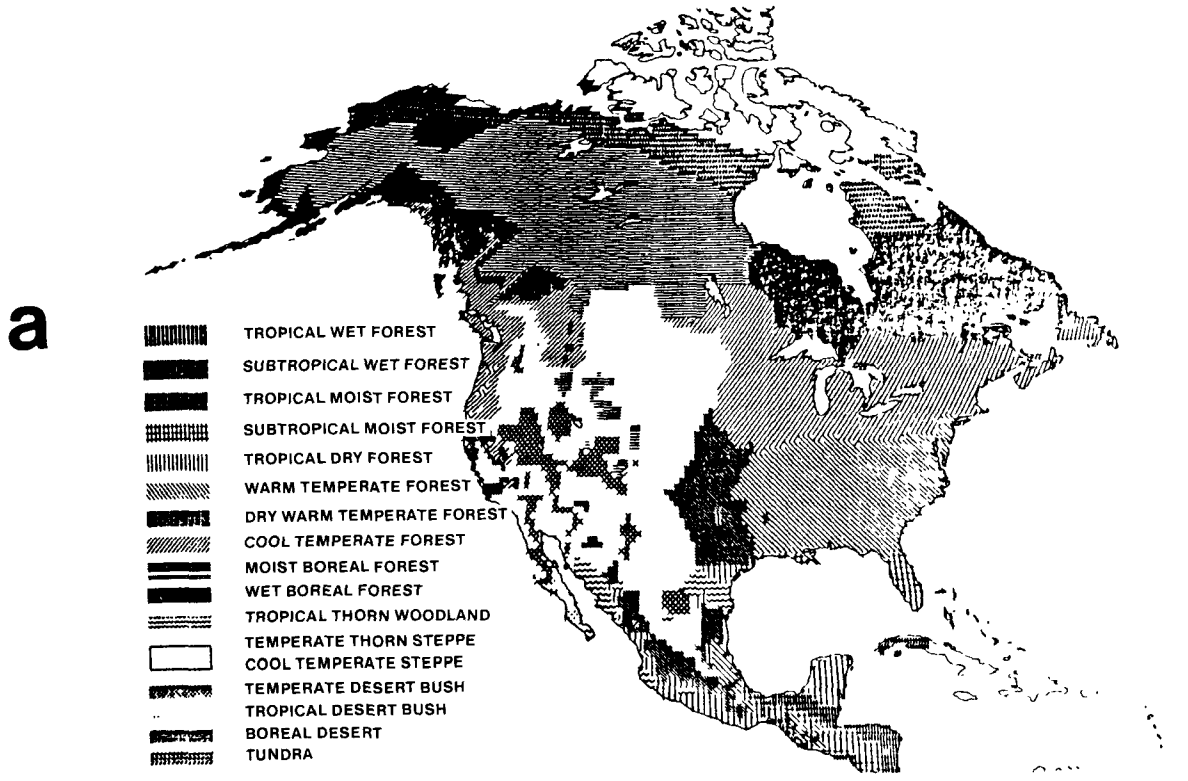
- Changes of Land Use to Optimize Production. Because different crops respond differently to changes of climate and to various levels of fertilizer application under those climates, any attempt to maximize output of each crop while minimizing production costs is likely to identify quite different allocations of land to alternative crops under different climates. In the central region, European USSR, experiments for arbitrary increases in mean annual temperature, for example a 1°C increase, indicate an optimal land use which increases the area under winter wheat, corn, and vegetables while decreasing the allocation to spring-sown barley, oats, and potatoes (Table 1.) This pattern of land use begins to resemble that at present found further south in the USSR and points to the value of using regional analogs to

identify possible responses to climate changes, a point we shall return to later. Broadly similar experiments in Iceland have investigated the increase in carrying capacity of both improved grassland and unimproved rangeland, assuming unaltered technology (carrying capacity increases by two thirds or more under the GISS projections). Given that inputs are unchanged, estimates show that increases in carcass weight of sheep could be obtained at the 1980 stocking levels, or alternatively the 1980 capacity levels could be maintained with reduced inputs (Bergthorsoon et al. in Parry 1986).

- Changes of Land Use to Stabilize Production. Experiments by the PFRA in Saskatchewan have tested the efficacy of removing marginal cropland from production as a means of drought mitigation. Wheat crops on this land tend to be profitable in years of normal or above-normal rainfall but can cause major losses in dry years. The present work has identified previously unimproved land brought into wheat production over 1951-81. This amounts to about 14 percent of all present cropland. In the experiments this is converted back from wheat to pasture for beef cattle, and total provincial output from the new mix of land uses is compared with that from the present land use for a variety of drought and nondrought years (Williams and Oakes 1986).

EFFECTS ON FOREST ECOSYSTEMS AND TIMBER PRODUCTION

A spatial shift of climatic zones resulting from a change of climate would, all other things being equal, lead to a spatial shift of vegetation types. But the rate of response would depend on the rates of migration of the species. These vary from ten to one hundred meters per year for many cool-temperate forest species in Europe (Shugart et al. 1986). There is evidence that considerable changes in the distribution of forests have occurred as a result of climatic changes in the past. Shugart et al. cite the transformation from spruce-dominated to jack pine-dominated forests in eastern Minnesota about 10,000 years ago occurring over at most a few hundred, and perhaps in less than one hundred years. They also note the effect of smaller climatic episodes such as that of the Little Ice Age in the prairie-forest border region of Minnesota where an increase in precipitation caused a reduction in the frequency of fires, thus encouraging a forest with more large hardwood trees than the oak forest it replaced. More recently, we may note the effect of even a small fluctuation such as that of a series of warm summers in northern Scandinavia in the 1930s inducing a regeneration of the boreal forest at its northern limit and a measureable advance of the timber line (Shugart et al. 1986). If we ignore for the present our uncertainties surrounding the rates of climatic change that might occur as a result of increasing atmospheric CO_2 and also the rates of migration of forest species in response to an altered climate, we can consider the equilibrium locations of forests that can be predicted for a given scenario of climatic conditions. Emanuel, Shugart, and Stevenson (1985) have mapped the changes in vegetation as classified by Holdridge Lifezones that would result from altered temperature and precipitation values for the Manabe and Stouffer (1980) 2 x CO_2 climatic changes scenario. Values from the Manabe and Stouffer experiment, which was for quadrupled CO_2, were halved to approximate values for doubled CO_2. Comparison of the base climate and doubled CO_2 maps shows a 37 percent decrease in the areal extent of the boreal forest, which is replaced at its southern edge by cool temperate step and to a lesser degree by cool boreal forest (Figure 14).



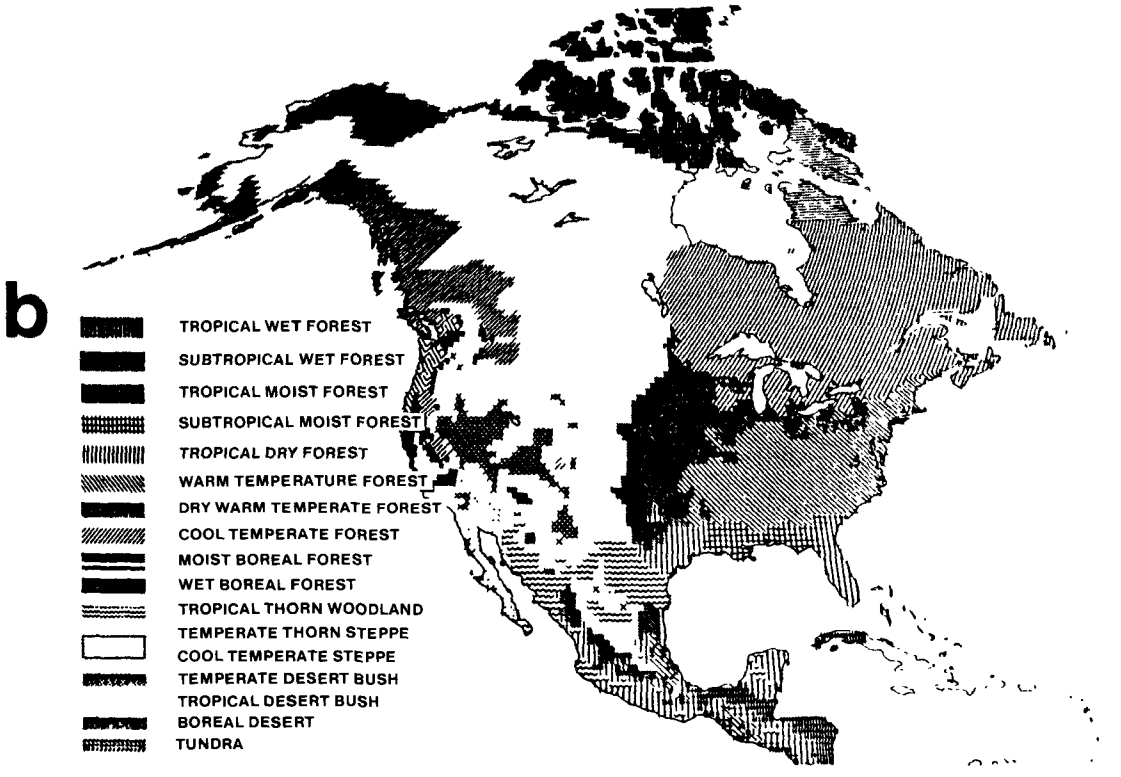


Figure 14. Holdridge Classification of N. America: a) base case b) with biotemperature increased to reflect climate simulated under elevated atmospheric CO_2 concentration. (Emanuel et al. 1985)

More insight into how forests might respond to changes of climate can probably be achieved by running computer simulations of forest growth, appropriately validated against independent data, under altered climates. The general results of the study have been summarized by Shugart et al. (1986) as follows:

- Slower growth of most deciduous tree species throughout much of their geographical range;
- A dieback of many dominant trees particularly in the transition between boreal and deciduous forest;
- An invasion of the southern boreal forest by temperate deciduous trees that is delayed by the presence of the boreal species; and
- A shift in the overall pattern of forest vegetation that resembled the pattern obtained from the Holdridge experiments by Emanuel, Shugart, and Stevenson (1985) and with a time lag of up to 300 years.

Some preliminary studies have recently been undertaken to consider the economic implications of these kinds of large-scale spatial shifts of forest types. As in the case of assessing economic impacts in agriculture, the task is one of using outputs from a general circulation model for doubled CO_2 experiment with a simple growth model and then using the estimates of changes in growth and forest area as inputs to an economic model. In the first part of the study, Kauppi and Posch (1985) correlated the location of the boreal forest with minimum and maximum effective temperature sum (ETS) requirements. They remapped the ETS boundaries for the projected climate and inferred the northward displacement of the boreal forest. From these maps Binkley (in Parry et al. 1986) has calculated, country by country, the change in productive areas as taiga areas become warm enough to support forest ecosystems and also the increase in growth on extant forest lands (Table 4). Using these new data, the IIASA global forest sector model, which projects production, consumption, prices, and trade of sixteen forest products in eighteen countries on the basis of forest growth, timber supply, processing facilities, and final demand was solved for a fifty-year projection horizon to provide estimates of changes in price, harvest, and income from timber sales. In general, timber producers in northern regions benefit by the warmed climate, although the size of the benefit is small except in Finland. Income from timber sales declines for all producing countries except Finland and Canada, as a result of substantial price falls. To illustrate, while the quantity of coniferous sawlogs harvested in Sweden increased by 24.5 percent, prices fell by 14.9 percent and income by 7.6 percent. For Finland the figures were +63.2, -8.6, and +22.4 percent, respectively. Full details are reported in Binkley.

Table 4. Impact of 2 x CO_2 on forest growth and area.

	Increase in forest area (%)	Growth: Current[a]	Growth: $2xCO_2$[a]	Growth: % increase
Finland	25.0	3.15 (3.18)[b]	5.45	73.0
Sweden	16.7	3.90 (3.01)	5.90	51.3
Norway	0.0	2.51 (2.40)	5.63	124.3
USSR	85.0	1.82 (1.41)	3.20	75.8
Canada				
East	22.2	1.89 (1.60)	4.47	136.5
West	36.8	2.21 (2.13)	3.53	59.7

a: m^3/ha/yr, based on the Kauppi and Posch (1986) growth model and temperature data interpolated on a 4° x 5° latitude/longitude grid by Shutz and Gabes (1971).

b: (), Estimates of current growth, m^3/ha/yr (Binkley and Dykstra 1985, Table 23.5).

RESEARCH PRIORITIES

We summarize in Figure 15 and its accompanying notes the direction that future research should take. Four main needs emerge. First, we require more specific and user-oriented information regarding climatic change (its likelihood, nature, magnitude, areal extent, duration, and most important, rate of onset). This information needs to be expressed in terms readily applicable to the user (and often as derived parameters such as date of first and last frost, days of heat stress, etc.), which would enable agroclimatic measures, such as length of growing season, to be more readily assessed. It is also important that information on variability be available to provide estimates of possible changes in those extreme conditions that we have seen to be important in agricultural decision-making.

Second, an important path of climatic impact on the most climate-sensitive sectors of our society (farming, fishing, and forestry) is an indirect one, i.e., they occur through changes in other physical systems (soil chemistry, and ocean currents, agricultural pests and diseases, and their vectors). Although we have barely begun to grasp these interactions, they clearly have a major influence on some production systems. The collapse of the Peruvian anchovy fishery as a result of the 1972 El Nino is one example. Probably more widespread is the effect of climatic conditions on disease. Outbreaks of many plant diseases (such as potato blight, wheat rust, etc.) are triggered by specific weather conditions. Climatic changes that affect the frequency of these conditions could alter the incidence of such outbreaks.

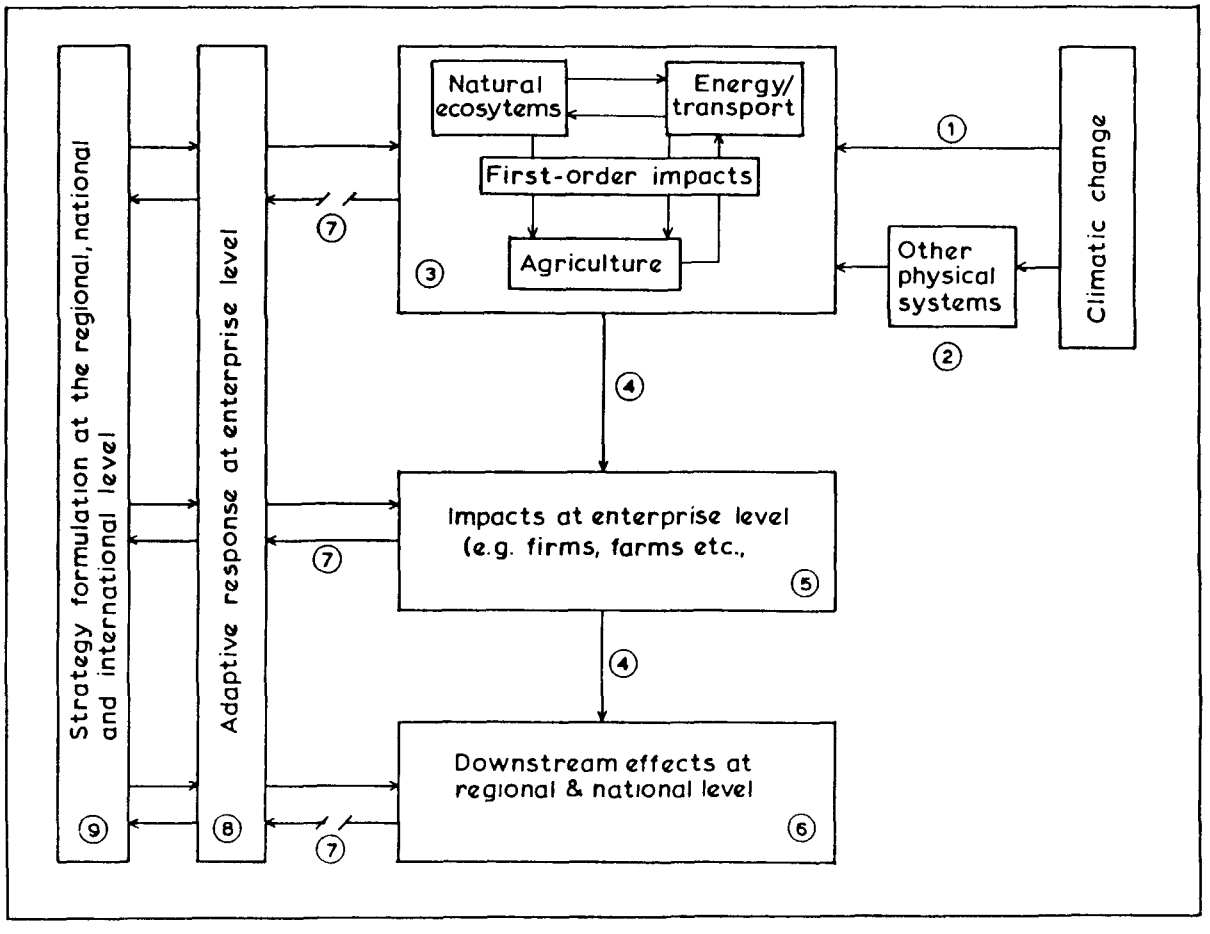


Figure 15. Some Research Priorities for Climate Impact Assessment:

1) More appropriate data
2) Better understanding of relationships between climate and changes in other physical systems
3) Better understanding of first-order impact
4) Greater precision in tracing downstream effects
5),6) Greater precision in simulating impacts at enterprise and regional levels. Better understanding of
7) Perception of effects,
8) Adaptive responses at enterprise level
9) Strategy formulation at regional, national, and international levels (Parry 1986).

Furthermore, we need to specify with greater precision the interaction between climate and other resources in the primary sector, by modeling empirically or by simulation crop-climate and timber-climate relationships. It should then be possible to trace, with greater confidence, the downstream effects of these first-other impacts on other sectors of economy and society, by reference to a hierarchy of the three types of models we have considered: climatic, impact, and economic.

Finally and, perhaps most important, we need to explore in greater detail the range of technological and policy adjustments available in agriculture in order to evaluate their efficiency in mitigating negative impacts or exploiting new options offered by changes of climate.

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The Water Resource Impact of Future Climate Change and Variability

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ABSTRACT

An altered availability of water will be one of the more obvious impacts of climatic change. This paper describes methods and models that have been used by hydrologists to try to forecast the effect of climatic change on the availability of water for human consumption, irrigation, power production, effluent dilution, and navigation. This assessment requires two steps; the first concerns impact on hydrological variables such as annual runoff; the second is required to assess the impact in human terms and expresses the hydrological variables in terms that quantify the exploitable fraction of the runoff.

This paper surveys the literature on both parts of this process. Causal, conceptual, and empirical models have been used to translate GCM and analogue climate scenarios into hydrological terms. Conceptual and empirical models have been applied to the further task of modeling the consequences to water resource outputs, particularly the performance of storage reservoirs. In an alternative approach an empirical model based upon the storage yield diagram is used to quantify the impact on reservoir reliability of given changes to the mean and variability of reservoir inflows. To extend this approach to accommodate climatic rather than hydrological change, the use of comparative hydrology techniques is advocated in which a future climate at a point is likened to the current climate elsewhere.

The advantages and shortcomings of the various approaches are enumerated, and these give rise to a list of research suggestions and strategies for future impact studies. The few papers and reports devoted to the subject clearly indicate that too little attention has been given to the problem in the past. Interest has begun to increase since the scientific consensus on climatic change appears to have centered on a global warming induced by radiatively active gases. International organizations have an important role in coordinating the necessary effort.

HYDROLOGY, WATER RESOURCES AND CLIMATE

Scope of Paper

This paper consists primarily of a survey of the literature on hydrological and water resource impacts of climatic change. The paper comments on the status of the methods and suggests further necessary research. Water resource impacts are clearly a relatively unworked area: only twenty-one papers and reports have been uncovered that concern themselves with future changes.

However, hydrologists have not ignored the climatic change issue and considerable literature exists on paleohydrology in which actual and surrogate hydrological records are used to detect past climatic fluctuations. Hydrologists also contribute to the general study of climatic change through their mathematical descriptions of hydrological process in global atmospheric circulation models (GCMs). These two topics are not covered in any detail in this survey.

The following subsections distinguish hydrology from water resources and describe hydrological measures that may be used to quantify water resource problems. The section on hydrological modeling for impact studies is concerned with the types of climate-hydrology transfer functions that have been used in studies of impacts on catchment response. Readers unaccustomed to hydrological modeling may wish to limit their reading to introductory and closing paragraphs, i.e., postscripts. The section on sensitivity of reservoir reliability to climate change deals with those few papers that focus directly on water resource impacts, in each case through its effect on reservoir performance. The section on research requirements lists requirements revealed by this survey and describes the role of international organizations in coordinating climate impact research.

The Distinction Between Hydrology and Water Resources

The subject areas of meteorology occupy neighboring segments of the familiar water cycle diagram. Hydrology is concerned with the near-land phase of the cycle and follows the progress of moisture from vegetation canopy level, through the soil, into aquifers and watercourses, while losing sight of it as it enters the sea. Analytical techniques span a range of complexities reminiscent of the zero to three dimensional atmospheric models of meteorology. There is also a branch of the science equivalent to climatology in which the hydrological regime is characterized statistically through measures of the mean and variability of such elements as flood, drought, aquifer state, or soil moisture deficit.

This climatological treatment rather than the description of processes is of most interest to the water resource planner. Until recently the planner and the hydrologist have not been distinct but increasingly the two have diverged as water resource science has introduced techniques drawn from other disciplines such as economics and administration. The planner's attention is focused strictly on the fraction of the water that is capable of exploitation--most critically for human consumption, but also for hydropower, cooling, effluent disposal, irrigation, navigation, and amenity. Thus while all natural water is of hydrological interest, only water that is available at

the time and place required, and in suitable quantity and quality, is of water resources interest.

It is helpful to imagine the hydrological system as a transfer function whose outputs are forced by input meteorological variables. Similarly it is useful to think of water resources as a system in which hydrological inputs are transformed to water resource outputs. Since water resource projects tend to be site-specific, formulating general relationships between the inputs and outputs that encompass all projects is not possible. However, a limited number of characteristic hydrological relationships tend to be influential in determining the properties and performances of water resource schemes. By substituting such relationships for output from climate-hydrology-water resource models quantifying the water resources impact of climatic change becomes possible. The following subsection describes the most important of these characteristic hydrological relationships and considers three classic water resource problems.

Examples of Water Resource Variables

Water Storage. A very common instance is urban water supply from a local catchment. Often an incomplete match between availability and need occurs in that, although in annual average terms the attachment runoff may exceed the demand seasons and occasionally entire years occur during which the river cannot meet the demand. A reservoir stores excess water from periods when runoff exceeds demand in order to meet the town's requirements during such periods of deficit. The relationship characteristic of this problem is the storage yield diagram Figure 1 which shows the reservoir volume needed to supply a given continuous yield with a given level of security, here expressed as percentage failure rate.

Flood Risk. A second case concerns flood-prone land alongside a river. An upstream detention reservoir can contain excess water or the river's carrying capacity can be increased. The objective in either case is to increase the value of the land by reducing flood incidence. Peak discharges and hydrograph volumes are analyzed statistically as an initial step in the design process of devising a scheme that maximizes the margin of benefit over construction costs. Figure 2 shows the flood frequency curve which is the characteristic relationship for this class of problem.

River Abstraction. Many rivers receive and convey waste, so knowledge of their diluting capabilities is important. Interest here focuses on the proportion of time that the river flow drops below some threshold level representing the limiting condition for self-purification. The flow duration curve Figure 3 is the characteristic relationship for this problem. The same relationship applies to many other problems where water is abstracted directly from rivers such as run-of-river hydropower, and small irrigation and water supply projects.

In all three cases the high and low flows, i.e., hydrological extremes, determine the water resource decision. These examples are deliberately simplified--real cases mix elements from each. They may span more than single sources and demand points, and decisions often must take account of factors outside the domain of scientific hydrology. Nevertheless, for purposes of climatic change impact studies these examples and their characteristic relationships can substitute adequately for water resource decision variables.

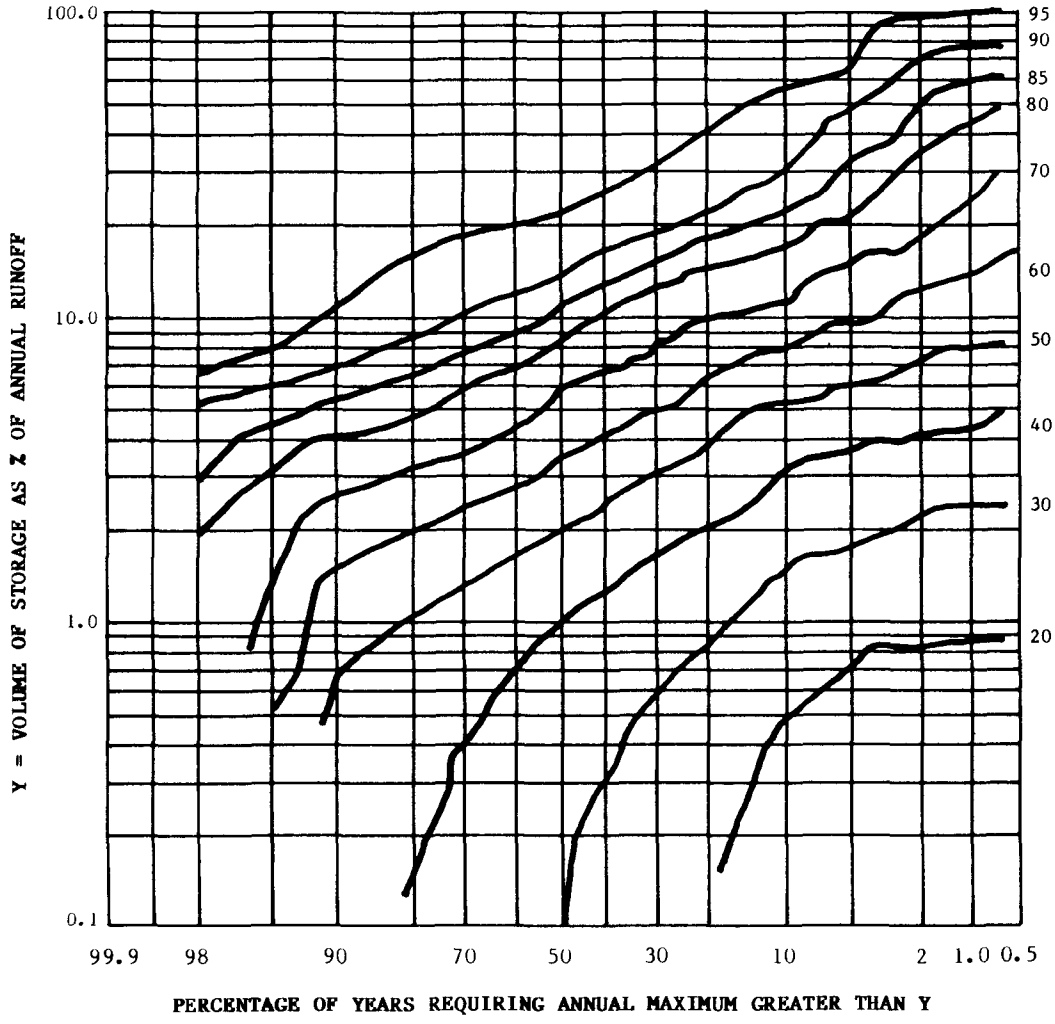

Figure 1. Storage yield diagram. The reservoir storage corresponding to a given constant demand and risk of failure can be read from the diagram. Alternative representations show failure risk as parameter (McMahon and Mein 1978).

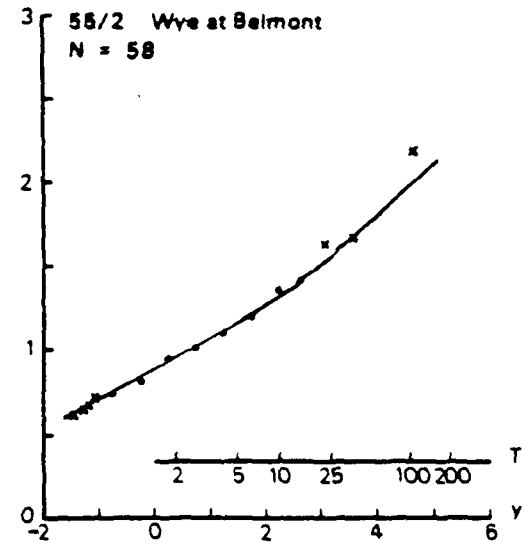

Figure 2. Flood frequency curve. The graph shows the average recurrence interval between exceedances of the given peak discharge. It can be drawn for flood volume as well as peak.

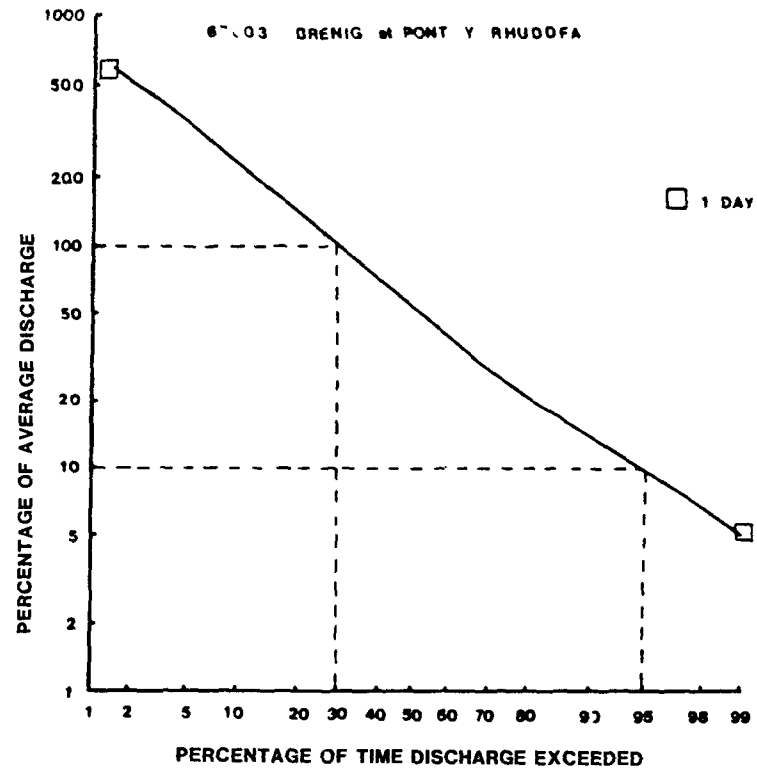

Figure 3. Flow duration curve. The graph shows the proportion of time the flow in the river exceeds the given level. It is the complement of the distribution function of flows.

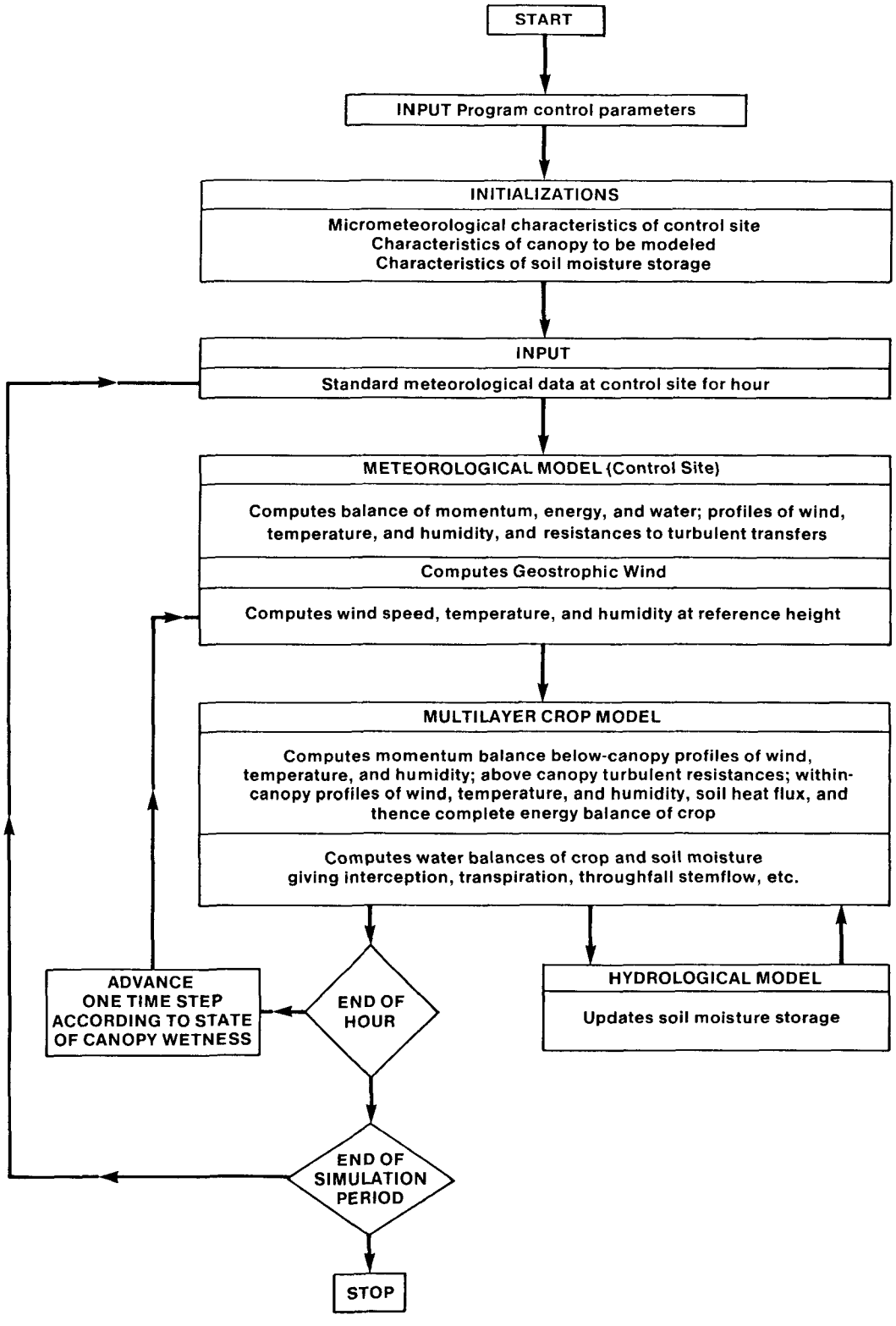

Figure 4. Illustration of water balance of small vegetated catchment (Lockwood 1985) physical model tends to concentrate attention on the crop and/or soil system.

HYDROLOGICAL MODELING FOR IMPACT STUDIES

Types of Hydrological Model

Models of the land phase of the water cycle vary considerably in their complexity and in their approximation to physical reality. Although categorization boundaries may be blurred, four types of model are recognized:

- At the leading edge are causal models which closely replicate physical processes within small segments of the cycle such as moisture flux at vegetated surfaces, below ground level, and in river channels.

- Models that operate at the catchment or aquifer unit scale--the relevant one for water resource studies--tend to lump processes into conceptual relations (the hydrological analogue of parameterizing sub-grid processes in GCMs).

- The third level of process simplification includes empirical models that exhibit little direct dependence on physical principles. Often they consist of statistical associations, e.g., regression equations, or of convolution relationships between input and output variables.

- The simplest type of model is the water balance. Although apparently based upon a physical principle--the conservation of mass--dynamical aspects of the processes which can be important at the annual time scale are neglected.

All four types of model have been used to assess the influence on runoff of climatic change and examples from the literature follow. In addition, models of the second and third type have been applied to water resource sensitivity studies and their application is described below. Although not directly related to the problem of impacts, there is considerable current interest in incorporating causal models, especially of soil moisture processes, within the structure of modern GCMs (Bauer et al. 1984; Brandyk, Dooge, and O'Kane 1985; Carson 1981; Hansen et al. 1983; Hunt 1985; Mintz 1981, 1984).

Causal Models

It is helpful here to consider the hydrological phase of the water cycle as a system whose inputs are precipitation and evaporation and whose output is river runoff. The inputs to this system therefore interface with state variables of climate models. The physics of the processes in the immediate vicinity of this interface are reasonably well understood. However, with very few exceptions, "downstream" processes are not readily expressible in physics terms; consider for example the complexities of the passage of a particle of water through vegetation toward a watercourse. As a consequence, models that adopt the more physical route describe processes on the plot, or even leaf, scale. Figure 4 shows one example, the MANTA model (Sellers and Lockwood 1981; Lockwood 1985), which closely replicates energy and moisture fluxes between ground and canopy level but devotes much less attention to the details of moisture movement within the "Hydrological Model" box.

Nemec (1983) following Lettau and Baradas (1973) has termed the output from this type of model as "climatonic runoff," and contrasts it with measured runoff which is the integration of the output of many differing spatial and temporal units through a complex of hillslope, subsurface, and channel processes.

The Briggs Model. An estimate of the impact of CO_2 doubling on runoff was made for the European Community area by Schnell (1984). His approach was to adapt the rain and evaporation component of the Briggs biomass potential model in which runoff is computed as the rainfall remaining after evapotranspiration and soil moisture replenishment. The British Meteorological Office GCM (BMO-GCM) provided the precipitation and temperate change inputs. Schnell recognizes the distinction between measured catchment runoff and the value generated from the model which is labeled "runoff potential." Figure 5, which maps the predicted change in average runoff due to CO_2 doubling, reveals an overall north to south trend in runoff reduction.

Evaporation Impact. Shuttleworth (1983) contemplates the use of causal models to describe the response of evaporation to changes in climate variables. He sounds a warning note to atmospheric modelers who incorporate land-surface interactions but neglect the certainty that vegetation will change in response to changes in precipitation and temperature. A quantitative basis for describing transitions between biomes that occupy adjacent climatic niches is needed and this limits predictions to small-scale or short-term climate change.

Conceptual Models

Conceptual models combine features of physics-based and empirical models of the land phase of the hydrological cycle. They are the workhorses of many water resource investigations because they incorporate sufficient physics to answer "what if" questions about change of land use, and they are flexible enough to link to mathematical models of water resource schemes. Meteorological time series are input to the models which yield hydrological time series, usually catchment runoff, as output. When the hydrological output is in turn put into the project description, then water resource decision variables, for example, a cash flow, can be generated from climatic inputs. Schaake and Kaczmarek (1979) suggested the use of models of this type to investigate climate impacts and two examples of their use in hydrological sensitivity tests are described below.

Sacramento Model. Figure 6 shows the algorithmic arrangement of the Sacramento model used by Nemec and Schaake (1982) in their studies of climate change impact. Instead of the detailed treatment of moisture and energy fluxes of causal models, the "boxes" of conceptual models contain relatively simple "step, branch, and ramp" formulations. The Sacramento model has been refined by the U.S. National Weather Service to serve nationally as a river flow forecasting tool. As a consequence it is structured to emphasize processes that control hydrograph geometry. Most of its parameters are determined from field experience and the model is calibrated to match recorded flows by adjusting the values of a few dominant parameters controlling the runoff response.

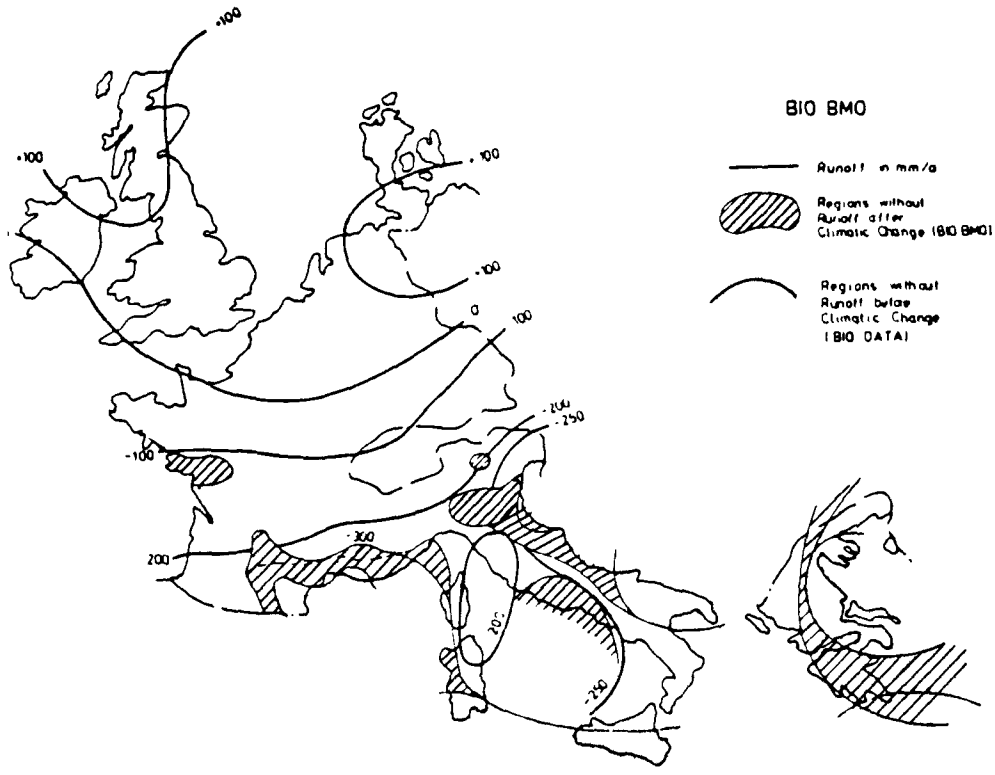

Figure 5. Generalized change in the runoff potential (mm) of western Europe following CO_2 doubling.

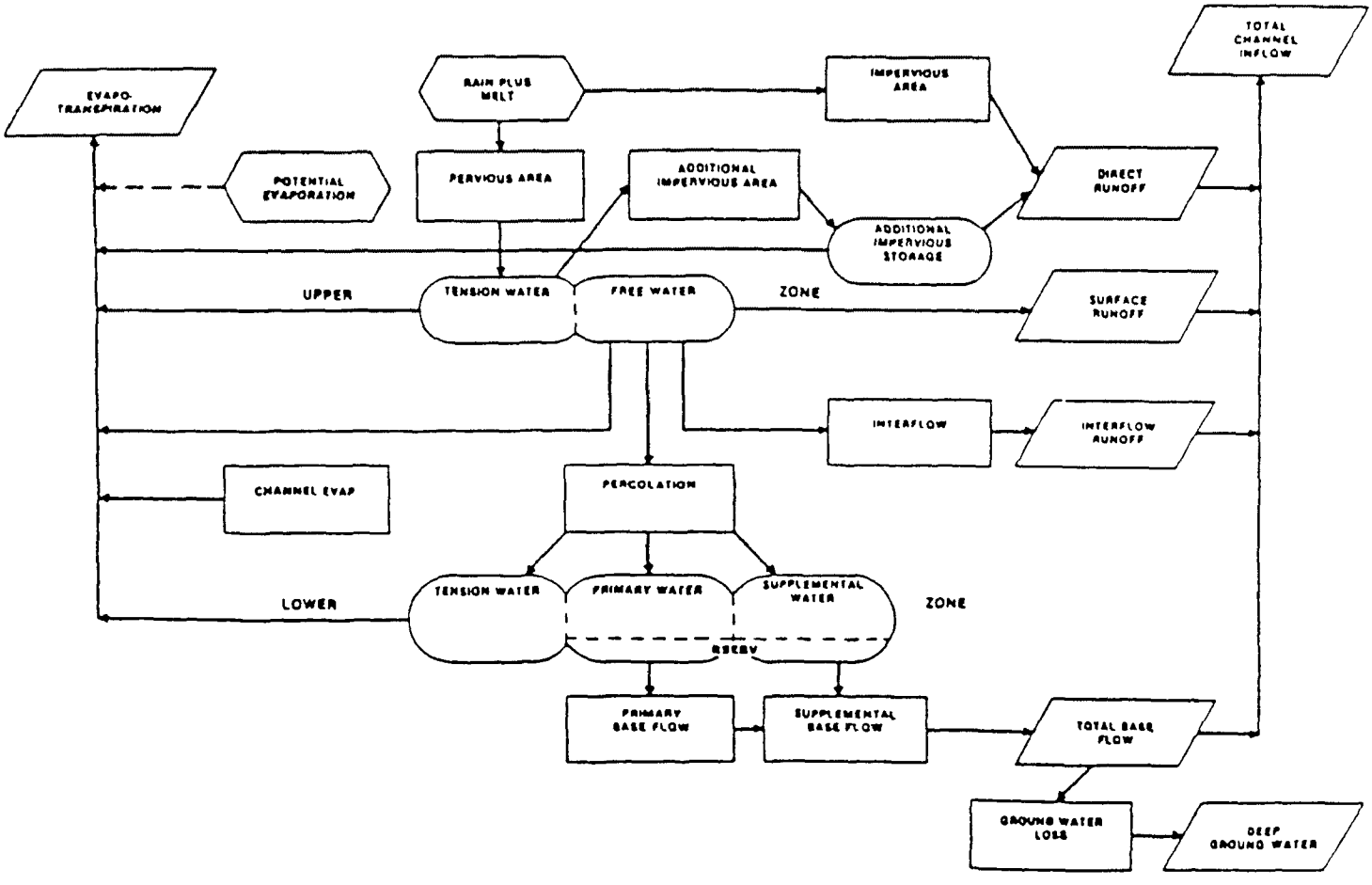

Figure 6. Flow chart for Sacramento model.

Results concerning runoff sensitivity only are discussed here: water resource sensitivity is included in the next major section. The Sacramento model was calibrated on the records of three rivers, two in the United States and an influent stream to Lake Victoria in the Upper Nile basin. Baseline statistics, primarily long-term mean runoff, were extracted from the model's output time series (see Table 1). The authors then considered a range of altered climate scenarios ranging from a 25 percent decrease to a 25 percent increase in rainfall, and from a 4 percent decrease to a 12 percent increase in potential evaporation (supposed equivalent to a 1°C decrease to a 3°C increase in surface air temperature). These adjustments were affected by scaling the input series, for example, by multiplying each rainfall value by 1.25.

Table 1. Percentage Change in Runoff from Base Due to Climatic Forcing

River	Precip. Base (mm)	Runoff Base (mm)	Runoff Ratio for Scenarios	
			+25,+12	-25.-4
Pease	540	11	+154%	-67%
Leaf	1314	409	+ 49%	-53%
Nzoia	1233	169	+170%	-75%

Taken from Figures 4 and 5 of Klemes and Nemec (1985) or interpolated from the original paper. First figures of scenario headings relate to the precipitation change from base, the second to evapotranspiration change.

The authors conclude that the changes in runoff fall outside the range of modeling error of the rainfall runoff process. The experiment is said to reveal the dominance of changes to precipitation and the extreme sensitivity of arid area catchments.

Klemes and Nemec (1985) subjected Nemec and Schaake's results to detailed statistical scrutiny. The principal concern appeared to be the statistical significance of the change, that is, whether or not the forecast runoffs lie outside the range of fluctuations that occur naturally under the current climate. By random sampling from a log-normal parent it was determined that changes in runoff due to precipitation changes of less than about 15 percent to 20 percent could not be distinguished from random fluctuations in the base record. This result is of course dependent on the record length used.

SHOLSIM Model. Aston (1984) considered the effect of CO_2 doubling on the hydrology of the study area in New South Wales, Australia. Although GCM predictions indicated no change in precipitation for the area, Aston anticipated an important impact due to the direct effect of CO_2 enrichment on vegetation--an increase in stomatal resistance with consequent reduction in transportation. Evidence presented in the paper shows that in many plants a

doubling of CO_2 concentration can lead to more than a two-fold increase in resistance. The scenario studied is for a doubling in resistance. An initial estimate based upon a combination equation for evaporation pointed to an increase in (climatonic) runoff of 85 percent.

Aston then pursued this finding through a conceptual model, SHOLSIM, of a 417 km^2 catchment. This model uses a much-simplified description of the evaporation process in which the overall effect of the resistance change was represented by doubling the gradient of the ratio of actual to potential evapotranspiration (AE to PE) with soil moisture content, and also by reducing the limiting rate at which transportation can occur. The result of the second influence amounted to a nearly 60 percent increase in runoff in an average year; the two influences together cause the modeled catchment runoff to increase by 90 percent, very much in accord with the causal model result.

Postscript on Conceptual Models. At first sight, the two studies are not easy to compare as the first is strictly an exercise in model sensitivity, while the second traces the effect of a specific climatic scenario. Aston considered the changes due to the direct effect of CO_2 enrichment to equate to an approximate halving of PE, well outside the nominal range considered in the Sacramento model simulations. However, Klemes and Nemec (1985) in their analysis of Nemec and Schaake's results revealed very strong linearities within the simulated series. Extrapolating (perhaps unreasonably) from these one finds a 1 percent increase in runoff for a 1 percent decrease in ETP for the Leaf river model, and by about twice this amount for the Pease and Nzoia river cases. This suggests that SHOLSIM and Sacramento model predictions are in reasonable accord.

It is important to remember that these results relate to model, not prototype, sensitivities. A good fit to the output series within the calibration period is no guarantee of a continued close match beyond it, nor of the correctness of the physical principles embodied in the model. Likewise statistical significance of the difference between the runoff records from two climate scenarios do not prove the truth of either.

However, the writer is unclear on the relevance of Klemes' and Nemec's (1985) requirement for establishing significance. When searching for discontinuities in past records it is clearly essential for statistical significance to be established. But in a prognostic study, it is beyond contention that changes in input create changes in output and changes, no matter how small, must be regard as real effects. In this context, lack of significance provides an interesting sidelight on the limitations imposed on an imaginary analyst searching for evidence of change in the past data by short records but serves no useful function in prognosis studies. Here the contentious issue is whether the model continues to replicate runoff correctly through a climatic change.

Neither Nemec's nor Aston's studies considered the compatibility of the precipitation with the hypothesized evaporation pattern, nor was it allowed that under the altered climate the rainfall may occur in different seasonal or storm patterns. Catchment response to intense periods of rainfall tends to a proportional rather than the subtractive response pattern implicit in the "bucket" model approach (see the section on water balance models).

Aston's study is more immediately helpful to planners in that it follows the logic of the specific climate change as far as current knowledge permits, although by substituting "resistance doubling" for "CO_2 doubling" some important issues are sidestepped. Contrary, or at least moderating, views on the direct CO_2 effect have appeared in the literature (e.g., Kramer 1981, quoted in Woodwell 1985) with the following implications and caveats:

- Plant species vary greatly in their reaction to CO_2 concentrations and it is reasonable to suppose that a plant mix would eventually develop that would exploit available resources
- The impact reduces as the plant matures
- Catchments are not fully vegetated
- Published experience relates to ideal conditions, e.g., greenhouses, where other stresses do not impinge
- "Greenhouse gases" other than CO_2 that may be responsible for climatic warming are not beneficial to plant development
- Nutrient availability and light conditions also control growth, and stomatal resistance is but one dependent state variable within a complex physiological process (Jones 1984).

Empirical Modeling

This class of model includes some that can operate in the time domain such as regression versions of conceptual models and others that consist of associations between average values but imitate in an empirical fashion the causal models discussed above.

Time Series Regression Approach. Nemec and Schaake (1982) reported that in 1979, two researchers named Beard and Maristany calibrated a regression relationship between seasonal runoff and climate data. They then scaled the precipitation and temperature input data to study the influence on runoff. The conclusions they reached are stated to be comparable with those quoted by Nemec and Schaake for their conceptual modeling approach. This can be explained by Klemes'and Nemec's (1985) observation of strong linearities in the monthly simulated runoff such that, although ostensibly nonlinear (Figure 6), the Sacramento model behaves as a regression equation with respect to its primary inputs.

Analysis of Historic Records. Palutikof, Wigley, and Lough (1984) used observed temperature, pressure, and precipitation data to investigate possible spatial and seasonal distributions of climatic change. Noting that the effect of the CO_2 increase is hemispherical warming, they argue that some appreciation of its effect could be gained from the contrast between the coldest (1901-20) and the warmest 20-year period (1934-53) in this century.

This type of analysis has been extended by this writer to consider runoff from major European basins. Table 2 shows the difference, warm-cold, between catchment rainfall and runoff.

Table 2. Seasonal Rainfall and Runoff Differences for Some European Basins (Difference - Standard Deviation Units)

Season	Thames	Loire	Rhone	Danube	Elbe	Oder	Vistula
Winter P	-0.3	+0/2	+0.3	0.0	+0.3	-0.4	-0.4
Q	+0.1	0.0	+0.1	-0.1	-0.4	-0.2	-0.2
Spring P	-0.2	-0.7	-0.7	-0.5	0.0	0.0	+0.1
Q	-0.2	-0.4	-0.8	+0.1	0.0	0.0	-0.2
Summer P	-0.6	-0.2	0.0	-0.1	+0.1	+0.2	0.0
Q	-0.6	-0.2	-0.5	-0.3	+0.1	0.0	-0.5
Autumn P	+0.8	-0.2	+0.5	-0.1	+0.4	+0.3	+0.3
Q	+0.1	-0.1	+0.2	-0.2	+0.1	+0.1	0.0

The rainfall values (P) were obtained by eye interpolation from maps presented in Palutikof, Wigley, and Lough (1984). The runoff (Q) data were prepared by the writer. The differences are expressed as a multiple of the seasonal standard deviation.

Total agreement between rainfall and river flow should not be expected because the latter is influenced by antecedent climatic conditions. However, agreement in terms of the sign of the change is good; only four of the twenty-eight show a reversal, and this is reduced further if a half-season lag is incorporated into the comparison. Apart from a small autumn increase, runoff appears to have reduced during this historical hemispherical warming; in the standardized units shown on Table 1, this was most marked in the spring and summer, but in absolute units the winter reduction was more important.

This approach does not by itself provide quantitative estimates of climate impacts. The most immediate question concerns the extent to which non-CO_2-induced warming can be represented, even in muted form, by contrasts between historic sequences in which CO_2 warming presumably played little part. Some support comes from the GCM findings of mid-latitude cooling and precipitation reduction (see Section 6.3.4 of Wigley, Jones, and Kelly, in press).

Another question of interest not directly answered by the approach is what fraction of the total CO_2-induced movement is represented by this historic change? In terms of the hemispherical temperature change the historical warming represented no more than 20 percent of the lower bound estimates of the CO_2-induced movement. The runoff reductions are very variable--11 mm in the Thames and 48 mm in the Rhone--overall of the order of 10 percent of the values shown in Figure 5.

Empirical Evaporation Model Approach. Cohen (1986) computes net runoff from the 766,000 km^2 catchment area of the Great Lakes for current and double CO_2 conditions. The heart of the model is an empirical formula, a modified form of the Thornthwaite model, from which monthly mean evaporation may be obtained from temperature and latitude. A soil model is also included from which

"climatonic" runoff is computed and then calibrated to accord with measured runoff.

Temperature patterns from two distinct GCMs (GISS and GFDL) were used to provide alternative sets of inputs for the Thornthwaite model. Some 32 percent of the catchment area consists of lakes, so open water evaporation is of great importance. Alternative wind scenarios had to be superimposed on the GCM results. The effect of CO_2 doubling varied between a 15 percent and 21 percent reduction in runoff with current or GCM generated winds for the different models. If a reduced wind speed was allowed, the runoff reduction was diminished to only 4 percent.

Cohen notes the seasonal differences but annual similarity between the results from the two models. Uncertainties regarding the future windfield over the lakes and lack of information on annual variability preclude any but very generalized conclusions about consequential water resource impacts.

Postscript on Empirical Models. Close inspection of the empirical procedures may leave an impression of "clutching at straws" by the authors. However, an analysis of their weaknesses reveals few that do not equally afflict the ostensibly more "respectable" causal and conceptual approaches. Those that can yield a time series, the regression, and Cohen's approaches have the advantage that they can provide inputs to water resource studies although in the regression case the series will differ from the base series in a purely linear fashion, a very unlikely eventuality.

Water Balance Models

The basic water balance equation is:

$$Q = P - E$$

where Q is runoff, P is precipitation, and E incorporates evaporation and other "losses." A few authors have used this relation to either directly or in modified form quantify the impact on Q of climatic change acting through P and E.

Average Rainfall Runoff Relations. Stockton and Boggess (1979) made use of relationships for predicting annual average losses from temperature and precipitation that had been derived by the U.S. Geological Survey (USGS). They investigated the effect on runoff of a GCM predicted 2°C temperature increase and 10 percent precipitation decrease across the United States. The implied sensitivities were checked by Revelle and Waggoner (1983) using an interannual regression based estimator of the sensitivity of the Colorado River annual runoff at Lea Ferry to those same changes. The agreement between the approaches was quite good; 40 percent reduction by regression compared with 44 percent by the earlier method. Over the entire study area with average precipitation of 30 cm and 4°C average temperature, the expected diminution in runoff is 35 percent. The most severely affected areas are those with lower rainfall and higher temperatures (see Waggoner, Volume 3).

Transpiration Effect. The conclusions of Revelle and Waggoner were questioned by Iso and Brazel (1984), who disputed the applicability of the USGS empirical relationships in a CO_2-enriched environment. When the effect of reduced

transpiration (conceptual models section) was allowed for the average 41 percent runoff reduction on five study basins predicted by the original method became a 42 percent increase. The authors list shortcomings in their analysis, though for the most part shared by the original analysis, and conclude with a salutory phrase that "plausible additions to state-of-the-art model studies of the CO_2 problem can dramatically alter current perceptions of future consequences."

Simple Water Balances. Wigley and Jones (1985) used equation 1 to investigate the representativeness of the apparently differing results quoted above as well as those of Rind and Lebedeff (1984) and Aston (1984). This approach invokes differential calculus to derive the proportional change in runoff, $\Delta Q/Q$, due to a given proportional change in precipitation, $\Delta P/P$, and evaporation, $\Delta E/E$. The large proportional increases quoted by Idso and Aston were shown to occur only in regions where P-E is small; in more temperate situations the rainfall change dominates and runoff can be expected to reduce. The approach has been extended by Glantz and Wigley (in press) who separate the contribution of deep infiltration loss from the evaporation terms. In the case where precipitation change dominates, the amplification factor between runoff and rainfall change is given as the reciprocal of the runoff coefficient, i.e., P/Q. In general the results indicate greater sensitivity than those predicted by Stockton and Boggess (1979).

Non-subtractive Models. The present writer has investigated the source of the difference between Wigley's and Stockton's conclusions. It was suspected that the main cause must be the imposition of a purely subtractive formulation for runoff formation in equation 1. Examination of observed catchment precipitation and loss values reveals tendencies such as those shown on Figure 7 for Cypriot rivers. The reduction in P-Q as Q increases can be interpreted as a transition from a proportional response to rainfall--runoff coefficient--to a subtractive response--constant losses.

The United States Soil Conservation Service (USSCS) model provides a suitable functional form for this type of response as it permits the runoff coefficient to vary according to the state of a notional storage. Although originally intended for "event" analysis the USSCS model can be modified for use with annual rainfall and runoff data.

$$Q = (P-I)^2/(P+S-I)$$

Parameter I represents initial abstraction and parameter S can be thought of as a maximum evaporation loss such as would occur if water supply were not limiting. A good fit to the Cypriot data of Figure 7 is achieved with S = 5I = 1350 mm.

Consider first the case of the simple water balance model of equation 1 with P = 600, E = 535, and Q = 65 mm. The runoff ratio is therefore 0.11, which, as explained above, gives rise to a nine-to-one amplification in runoff over rainfall change. Because equation 2 is nonlinear, no simple or general relationship exists between the sensitivity of an individual year to a given climatic adjustment and the average over all years. For illustrative purposes, however, it is sufficiently accurate to assume that the effect on an

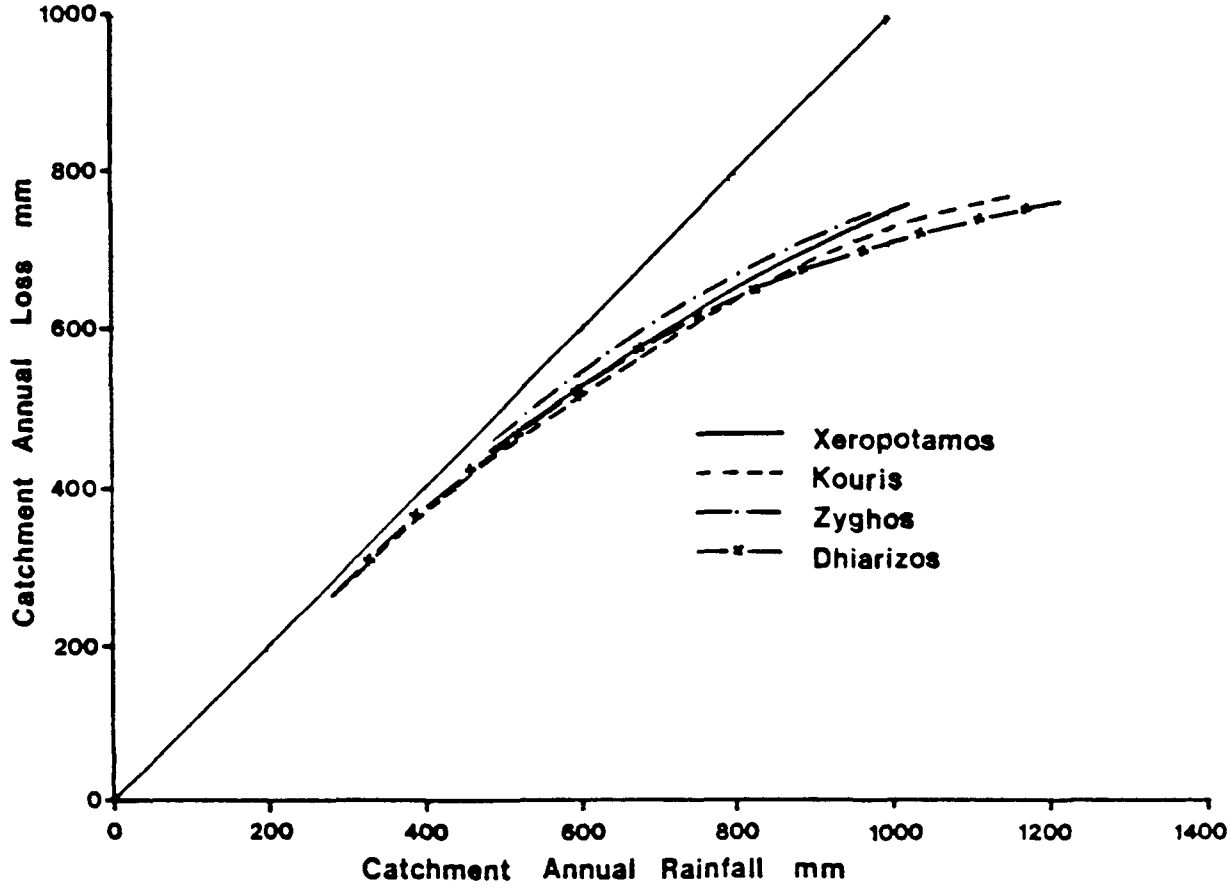

Figure 7. Rainfall/catchment loss diagram for rivers draining the Troodos mountains, Cyprus. This pattern is typical of semi-arid regions where annual rainfall is seasonal and varies from 300 to 1000 mm.

individual year experiencing average rainfall will represent the average over all years. Taking increments of equation 1 gives

$$\frac{\Delta Q}{Q} = \frac{2P(1-\mu\varepsilon i/\varepsilon p)}{(P-I)} + \frac{P(1+4\mu\varepsilon i/\varepsilon p)}{(P+4I)}$$

where μ is the ratio of I to P and εi and εp are relative changes in I and P. With P = 600 as before equation 3 yields an amplification factor between runoff and precipitation change of 3.3, very much smaller than that given by the purely subtractive model of equation 1. Under the runoff relation of equation 2 the amplification is controlled by μ rather than by the runoff coefficient.

Postscript on Water Balance Models. The use of time averages and simple formula have the advantages that they can be easily calibrated against observed data. Nevertheless, little agreement exists between the results obtained by the various approaches. The disparities are as much due to differences in mathematical structure as to the uncertainties that accompany extrapolation to a different climatic regime. This was demonstrated by contrasting a subtractive and a partially proportionate model. It is significant that as well as equation 1 many other models, implicitly or explicitly, employ a formulation in which runoff appears as a residual from rainfall. This property is shared also by the structure of the Sacramento model (Figure 6) which may therefore also be expected to exaggerate the impact on low-runoff catchments. This writer also cannot agree with Glantz and Wigley's structure that extra caution is required "in accepting results . . . if these results appear to be at odds with simple water budget calculations." Equation 1 does not express a dynamical truth and the year-on-year interaction between P and E needs to be considered in climatic impact studies.

SENSITIVITY OF RESERVOIR RELIABILITY TO CLIMATE CHANGE

Introduction

Despite its popularity as a paper or report title, very few authors consider impacts to water resource variables in the sense that the section on the distinction between hydrology and water resources describes. Impacts may be divided into the altered requirement for water due to climatic change and the altered availability of water to meet those demands. Those authors who have attempted to quantify water resource impact have used the reliability of reservoir supply (Figure 1) so it is that measure that is discussed here.

Effect on Demand

The projection of future demand for water is an art practiced at various levels of sophistication by water supply authorities. Single purpose projects such as irrigation or power supply pose a relatively simple problem in demand forecasting. However, most planning problems are multidimensional and fraught with uncertainties even within the existing climatic regime. The imposition of trend on an already fluctuating climate was considered by Schwartz (1977) as "additional fuel for the 'let's wait and see' style of facilities planning."

In the same report Lofting and Davis (1977) considered the definition of demand as it relates to water supply noting that it is led by supply and not subject to the same checks and balances encountered with conventional industrial products and services. In their paper, they analyze the demands of various users separately and make projections to the year 2020 for the United States. They consider the impact of climatic change through demand pattern in the agricultural sector alone.

Hargreaves (1981) considered irrigation project planning specifically. He reduces the problem to one of estimating the change in potential evapotranspiration (PE), this being regarded as the sole determining influence on water demand. His analysis of GCM results leads to a latitude related increase in PE of 16 percent to 63 percent, which is to be fed into U.S. standard procedures for computing irrigation need. As admitted, this assessment makes no allowance for changes in clouds (affecting radiation), precipitation, or photosynthesis.

Cohen (1986) presents in a flowchart the many interconnected components of climate impact assessment in his Great Lakes study. As well as the direct effects on consumption of an altered temperature, many indirect effects are listed. For power production these may take the form of a switch from water resources for hydropower to cooling water for coal, oil, or nuclear power stations. Crops may require less water in a CO_2-enriched world, and if the study area occupies a zone where warming occurs then enhanced biological activity requires a lesser dilution of effluents.

Glantz and Wigley (in press) report briefly on demand impact and refer to recent more comprehensive work by Callaway and Currie (1986) who divide the impact sector by sector.

Effect on Availability

Schwartz' Methods. Schwartz (1977) offers three approaches to the task of evaluating the water supply impact:

- Case studies of particular schemes with special reference to their reaction to past anomalies
- Speculation about impact on broad classes of system attributes to types of change in runoff pattern
- Behavior analysis of water supply facilities with synthetically generated inflow sequences.

The first approach, also used by Glantz and Wigley (in press), reveals important issues to be treated in the second and third approaches, but does not provide any quantitative estimate of impacts.

The result from the second approach was an "impact matrix" showing the direction of change in run-of-river, reservoir, and groundwater yield due to a decrease in mean streamflow, and increase in variance, skewness, and persistence. Other attributes which were considered included water quality, system reliability, operation costs, and flexibility to change.

In the third approach Monte Carlo simulation was used to generate 1000 year synthetic traces. Eight scenarios were considered with two levels of decrease in the mean, and increase in variance, skewness, and persistence. The flow sequences were input to a reservoir whose capacity had been determined to give 5 percent probability of failure under present-day conditions. The most severe effect of the eight was the case of a reduction in the log-mean of 20 percent but even this reduced the reliability only to 91 percent. Restoring the reliability to the original 95 percent reduced the yield by 20 percent.

Sacramento Model. Nemec and Schaake (1982) used their adjusted data series (empirical modeling section) as recommended by Schaake and Kaczmarek (1979) by treating them as inflows to a storage reservoir. They investigated the change in yield from a given storage and the change in storage to maintain a given yield. In both cases the reliability was held constant. Klemes and Nemec (1985) extended the results to consider how the reliability of supply from an existing reservoir was affected by the same range of changes.

Figure 8a shows some amplification in the yield change over precipitation change but the more dramatic effect occurred with the storage change for a given yield. Figure 8b shows highly nonlinear results with up to 20:1 amplification over rainfall change. As with the runoff experiments the precipitation change was more critical than the evaporation change. For a drier climate, the drop in reliability may be more significant than the drop in precipitation; this effect is greatest on river systems with a high level of development. In one of the experiments, a yield equivalent to over three-quarters of the mean flow was assumed. To provide 95 percent supply reliability this requires a 600 million m^3 storage. Under the drier climatic regime this reliability drops to below 25 percent, i.e., in three out of every four months the desired yield would be unavailable.

Empirical Approach. The United Kingdom Low Flow Studies (Institute of Hydrology 1980) demonstrated that the storage yield diagram within a region can be stabilized if the yield is expressed as a point on the flow duration curve (FDC). Figure 9 shows such curves for Britain, Malawi, and Southeast Germany. Despite considerable differences among the three regions it is notable that the curves are not entirely dissimilar.

Beran (1984) considered that such diagrams permit a preliminary estimation of the impact of climatic change on reservoir performance. Like Schwartz (1977) he assumed that climatic change would be effected through changes in the mean and variability of discharge. No change in the standardized storage yield diagram was thought necessary.

Consider a reservoir in Malawi designed for a yield equivalent to the 80 percentile point on the FDC and supplied with 90 percent reliability, i.e., 10 percent failure rate. The effect of a change in mean runoff is straightforward--a decrease of 20 percent leads to an equal decrease in yield. The effect on failure rate is more complex as it depends on the gradient of the FDC. Figure 9 indicates a storage requirement equal to 2 percent of the annual runoff. If the average runoff were to decrease by 20 percent then this reservoir would appear to hold 2.5 percent of the revised annual runoff. For most influent streams to Lake Malawi the yield would now correspond to between the 70 and 75 percentile points on the revised FDC.

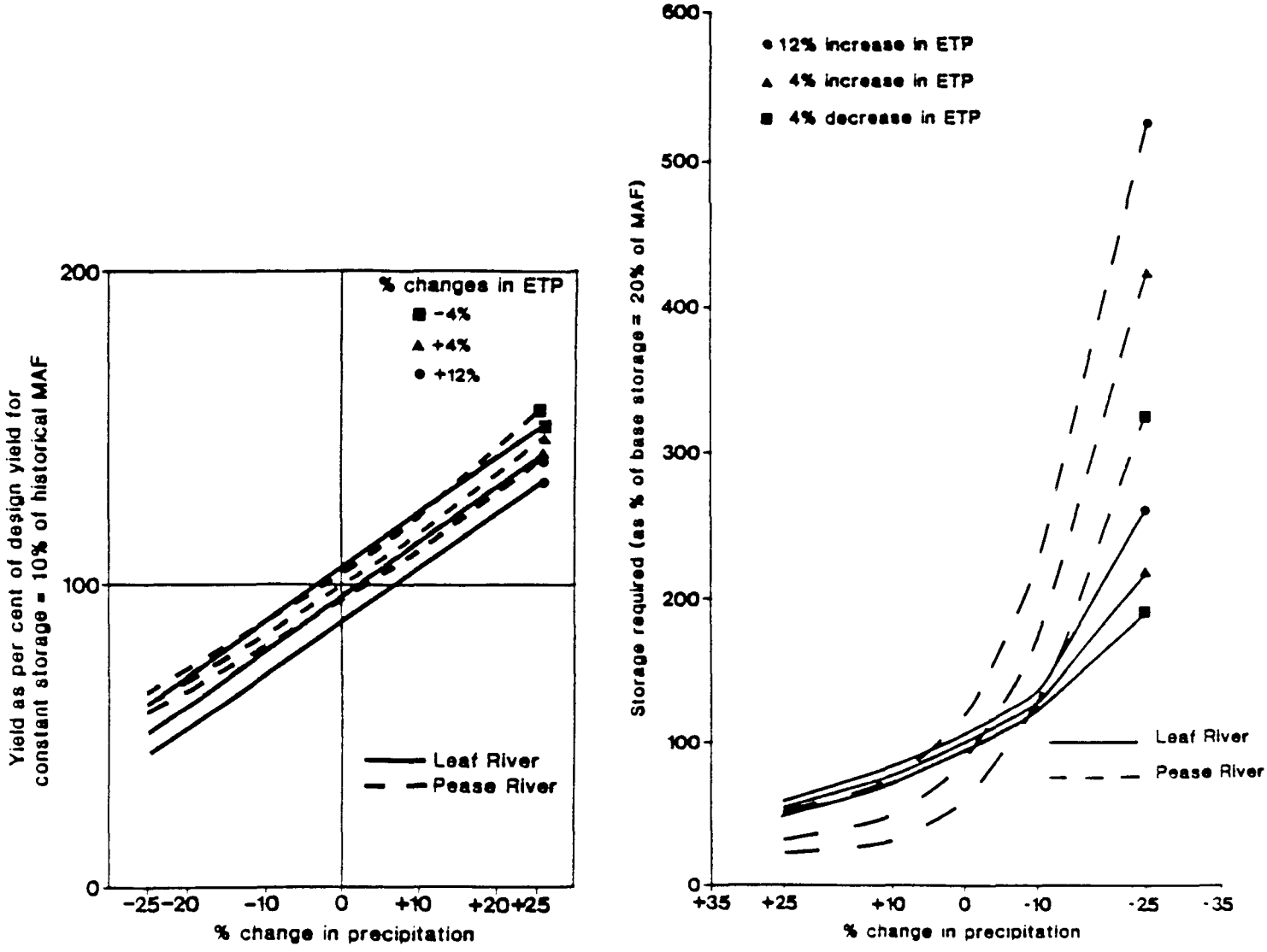

Figure 8. Effect of changes in precipitation and evaporation on (a) reservoir yield for a fixed storage equivalent to 10% of annual runoff and fixed reliability of 90%; and (b) reservoir storage for a fixed yield equivalent to 20% of mean discharge and fixed reliability.

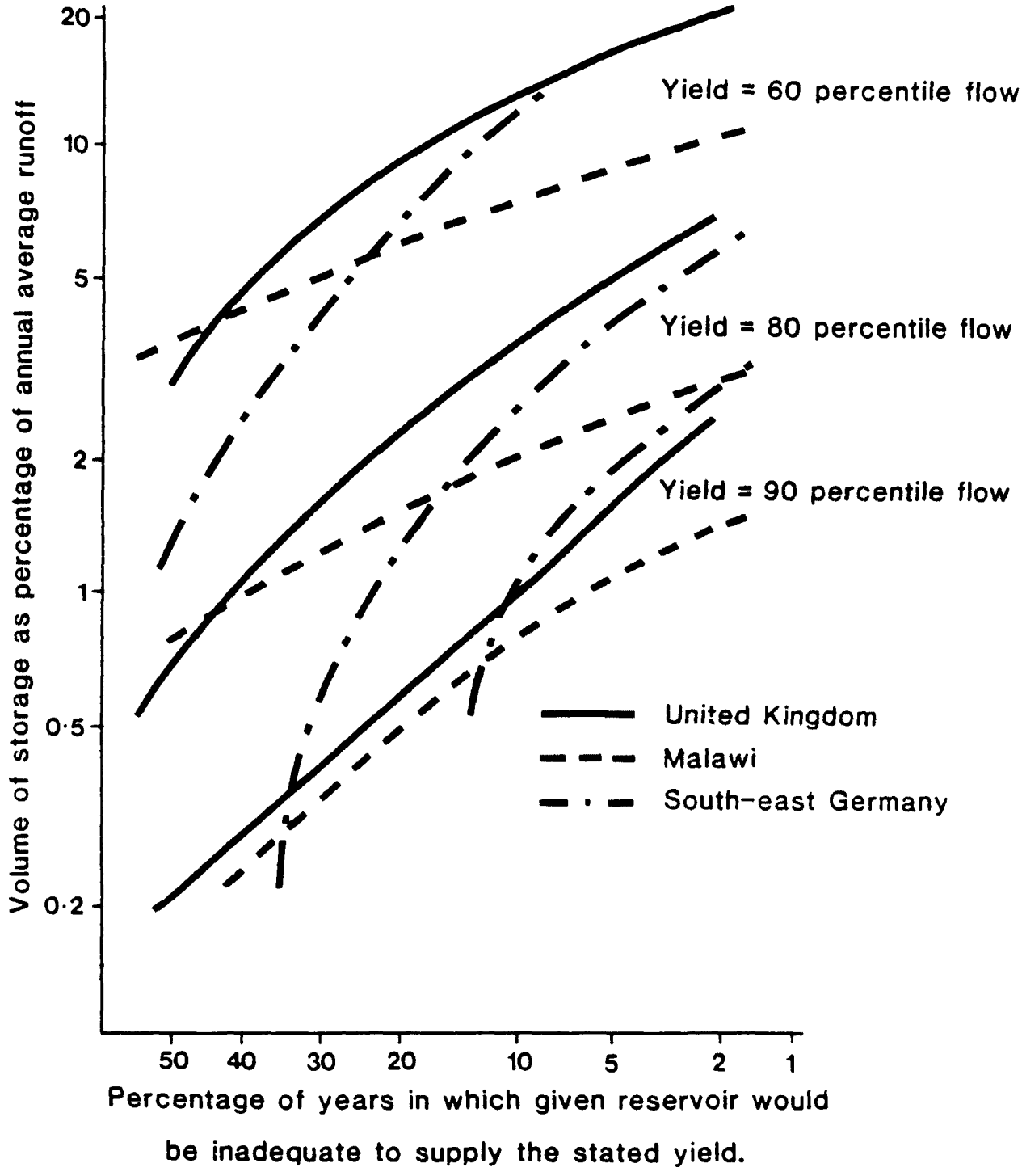

Figure 9. Standardized storage yield diagrams for United Kingdom and Malawi. This differs from Figure 1 only in that the yield is expressed as a percentile on the flow duration curve.

Reentering Figure 9 with the revised yield and storage values results in a postchange reliability of 70 percent equivalent to a drop from a 10-year to a three-year return period of failure.

The effect of increased variability can be more dramatic. If the same reservoir were subjected to a 20 percent increase in the coefficient of variation (proportional to the gradient of the FDC on lognormal paper) the percentile corresponding to the given yield reduces from 80 percent to 70 percent, which without the compensating effect of an apparent storage increase gives rise to a four-fold diminution in reliability.

The impact in the United Kingdom and Germany is more complex as the range of FDC types is much wider. The largest impact is on rivers with steep FDCs corresponding to catchments of impermeable geology and low base flow support. Most upland reservoirs in the United Kingdom occupy catchments of this type. The impact is aggravated by the relative steepness of the storage yield lines.

Figure 9 applies principally to smaller reservoirs where over-year storage is seldom required. McMahon and Mein have derived simple relationships expressing reservoir volumes as a function of the interannual variability of the inflow series for use in more variable climatic regimes where over-year storage is common. These indicate amplifications between 1.5 and 2 between inflow variability and storage requirements; in other words a 10 percent increase in variability leads to a 15 to 20 percent increase in reservoir volume requirement (Beran 1984).

Use of Comparative Hydrology Approach. Of the three quantitative procedures, only the Sacramento model currently uses climatic inputs; even so, no specific climate model-based scenario was considered. The other quoted procedures, Schwartz' and Beran's, did not employ climatic inputs but were based upon predefined changes in the runoff regime. This could have been remedied by directly relating the salient statistics used in those approaches--storage yield, skewness, and persistence--to controlling climatic statistics.

The technique of "comparative hydrology" is one means for deriving such connections in which hydrological characteristics such as those listed above are computed from the available hydrological data and then compared with corresponding quantities from different climatic regions. This step will introduce further uncertainty and in this respect is inferior to a model that operates in the time domain and that uses climatic inputs directly.

All the examples described in the previous section assumed that the inputs would change but the internal model structure and relationships would be preserved over the climatic change. While such a standpoint may serve for a preliminary assessment any fuller impact evaluation should assume that the transfer function itself may change with the climate.

Again the comparative hydrology approach may be useful. If it is possible to express climatic change scenarios in terms such as "the future climate of Britain may be similar to the current climate of (for example) southeast Germany" then the current data for that region (Figure 9) will provide the necessary answers. This approach cannot readily be applied to the

conceptual model approach and in this respect the empirical approach is superior.

This is an approach that has already been employed in impact studies of food production by comparing climates within the North American midwest (Parry 1984). Quantitative methods of climate typology such as Litynski's (1983) procedure will be valuable in recognizing climatic analogs.

RESEARCH REQUIREMENTS

Introductory Remarks

A vast literature has accumulated on the topic of climatic change in general and impact studies in particular. The reference list at the end of this paper confirms that surprisingly little of this activity has concerned hydrological and water resource futures. Only twenty-one relevant papers have been discovered, the majority of which treat hydrological aspects only, mean annual runoff being the most commonly treated variable. Fewer than five papers consider water resource oriented variables in a quantitative way. Moreover, no consensus on preferred methods of attack is apparent from these few papers.

An obvious need therefore exists for more research, particularly impact studies of water resources, and the following subsection makes suggestions based upon this survey. An international framework exists through the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) for impact studies and relevant aspects of their programs are described below.

Research Topics

In the past, the main contribution by hydrologists to the climatic change issue has been to paleoclimate studies and land-phase process descriptions for GCMs. Engineering hydrology had tended to distance itself from the issue in the period when even the sign and time scale of projected change remained uncertain. Reaction was typified by one correspondent to Rodda, Sheckley, and Tan (1977): "water management policy could not be based on models with low explained variance." Since climate projections have centered on radiatively active gas-induced warming a little more attention has been given to water resource impact studies. The listed topics have been suggested primarily by shortcomings and uncertainties in the models that have been used so far.

Climate-Hydrology Transfer Function. This has been a long-term preoccupation of hydrological science for which climatic change studies provide yet further impetus. Models of all types need continued development particularly to inject increased physical content in conceptual models. To date models have tended to concentrate attention either on hydrograph generation or on soil processes. Such models need "balancing" to achieve a greater uniformity of process description.

Hydrology-Water Resource Transfer Function. There is a need for "type projects" on which to base experiments and test sensitivities. The three suggestions of this report retain their hydrological heritage but others are desirable that encompass more complex schemes. It is important that chosen

project descriptions be realistic and capable of transfer to a range of climatic and geographical regions.

Relationship Between Climatonic and Measured Runoff. Many of the more physically based models equate runoff with the drainage term in a crop model. Were general relations available that explained the spatial and temporal scale on which the two runoff types could be equated, or how one may be translated into the other, then greater practical use could be made of the causal model predictions. An extra benefit from this knowledge would be the ability to make direct use of GCM hydrological outputs.

Other Hydrology Variables. There has been a tendency to concentrate on runoff as the variable of prime interest. However, in certain circumstances other variables are of equal or greater importance and some may be more amenable to climate impact investigation. Actual and potential evaporation, soil moisture deficit, and groundwater recharge have a good claim for investigation. Other physical and chemical properties of water should also be studied, for example temperature and buffering capacity.

Effect of CO_2 Enrichment on Transpiration Rate. Although more properly a topic for plant physiologists rather than hydrologists, recent research has demonstrated the importance of this phenomenon on water resources impact. Statements are required about the likely vegetation response, and these (possibly alternative) views should be incorporated in impact models. One crucial issue is the transpiration response to increased CO_2 of different vegetation classes growing in an outdoor competitive environment. Another concerns the likelihood and time scale of biome adjustment to the opportunities presented by a new regime.

Historical Data. Scenarios based upon past periods of warming and cooling will remain for some time to come the most believable indicator of the likely regional and seasonal (i.e., sub-grid) pattern of climatic change. Further research is needed to extend the approach to water resource variables in different localities. It would be useful for standard regional sets to be made available based upon known contrasting periods in order to provide the test bed for sensitivity experiments and intercomparisons.

Model Intercomparisons. At a later time it will be important to set up controlled experiments along the lines of previous WMO intercomparisons of forecasting and snowmelt models to compare the capabilities of various models to forecast impacts on standard water resource schemes.

Empirical Approach and Comparative Hydrology. Diagrams such as the standardized storage yield diagram will probably retain their basic form over a climatic change. Further work is needed to produce such diagrams (as well as other diagrams and statistics representing different water resource problems) for climatic regions, to identify the major controls, and to quantify likely changes to stated climatic variation. Historic data from recent past warm and cool periods can provide temporal validation of the approach. There exists already a program within Unesco's "International Hydrology Pogramme" on comparative hydrology.

Water Budget Models. Useful insight has been obtained from simple formulations concerning mean values and annual totals. This paper presents ideas for generalizing their form to accommodate more closely the statistical dynamics of runoff on the annual scale. Further development is needed to apply them to temperate regions and to incorporate possible reduced transpiration and model inaccuracy.

Demand Forecasting. A more analytical approach is needed to demand forecasting through a period of climatic change. Direct and indirect effects should be enumerated and a judgment made about the direction of response.

Probabilistic Impact Forecasting. Even though the scientific community has now arrived at a consensus about the likely direction for the climate, much will remain uncertain about spatial and temporal details. By attaching weights to alternative scenarios and models, probabilistic statements could be made about the range of water resource impacts. Alternative design strategies could be tested in this way. For example, an important practical issue concerns the period of record that should be used for project evaluation--is it better to use the entire period of record, is it better to use a short but recent run of data, or should designers project forward in time to try to account for possible climatic changes? Data requirements for recognizing various levels of change should also flow from such an analysis.

Coupling of Water Resource and Other Impact Variables. Agricultural and energy impacts have a similar socioeconomic importance to water resource impacts and are also, to some extent, water dependent. Impact studies which could simultaneously encompass all three would be of value in assessing their relative importance in particular changed circumstances, and in ensuring mutual compatibility in policy determination.

International Programs

The international community has recognized the crucial importance of the climate issue. Perhaps the clearest statement yet to emerge was that issued by the UNEP/WMO/ICSU meeting at Villach in October 1985 (WMO 1986). This meeting asserted that the combined concentrations of "greenhouse" gases will be radiatively equivalent to a doubling of CO_2 concentration by as early as 2030 and this will lead to a global warming of between 1.50 and 4.5°C. There was little residual doubt that there would be profound effects on global ecosystems, agriculture, water resources, and sea ice, so governments were urged to support programs to improve knowledge and ameliorate effects.

The World Climate Programme instituted in 1979 following the World Climate Conference is the main agency for coordinating the international effort. This has four components: research, data, applications, and impact. This last component is being supervised by UNEP but is also strongly represented within WMO's Commission for Hydrology (CHy) through the World Climate Programme (Water).

The WCP is not solely concerned with the climatic change issue although this has become increasingly central to its activities, especially those of the WCRP. UNEP's programs so far have concentrated on food and climate variations, and more recently on ecosystem and societal impacts of climatic change. WCP (Water), largely organized within the WMO Commission for

Hydrology, has components corresponding to the main divisions of WCP. Research topics concern the use of long term hydrological data in the detection of past changes as well as contributions to the HAPEX and other WCRP experiments. Nemec's, Klemes', and Beran's studies cited here have all been conducted under WCP (Water) auspices.

SUMMARY AND CONCLUSIONS

Now that consensus has been reached on the likely direction of climate, at least in global terms, more effort must be given to projecting the likely hydrological and water resource impacts. In this paper, hydrological variables have been described which may substitute for water resource problems. Models of varying levels of complexity have been presented which allow climatic information to be translated into hydrological terms. Examples from the literature illustrate this process and have allowed a number of conclusions to be reached about fruitful avenues of future research.

Scale and process shortcomings in climate modeling still may radically alter forecasts insofar as they affect individual regions. For this reason it is considered that historical data from the study region should provide the base data for extrapolation in impact studies. In this approach salient hydrological properties are extracted from recently relatively cool and warm periods. The contrast between the two sets of statistics can be scaled up to conform to the projected climatic change.

No preference is expressed between models as all have strengths and drawbacks. Conceptual models are inevitably deficient in their physical description and offer no greater certainty of correct performance than much cruder water budget or empirical formulations. However, it is easier operationally to allow for a climatic change through adjustments to the inputs to a conceptual or regression model than empirical models such as the storage yield diagram or water budget which work with time average quantities. Nevertheless, because the latter can make use of climate scenarios based upon analog regions they also offer, through comparative hydrology, a powerful approach to answering impact questions.

Research suggestions that promote all approaches have been made together with a framework for intercomparisons. Researchers must remain vigilant to research elsewhere in climate science as surprises that may upturn forecasts are still possible. An example from the recent past is the possibility that water use by vegetation may be much inhibited in a CO_2-rich environment. Future surprises may emanate from sea-level changes, and from new knowledge on gas uptake by oceans and the effect of improved treatment of oceans, clouds, and soil moisture within GCMs.

Research findings from paleoclimatology and hydrology should also be studied closely for information on past analogs. One obstacle that still remains to acceptance of the CO_2 issue is that, despite an already considerable increase in the atmospheric concentration of radiatively active gases (possibly 20 percent, since preindustrial times), there has been no unequivocal and identifiable hydrological impact that cannot be explained in terms of random fluctuations.

This desirability for water impact studies to be part of the community of climatic change research gives it the character of "big science" in terms of the intellectual, experimental, and computational requirements. While scope exists for individual effort the greater dividends will come from concerted research by networks of laboratories operating within the general framework of the WCP.

ACKNOWLEDGEMENTS

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REVIEW AND ASSESSMENT

Determining the Options—The Role of UNEP in Addressing Global Issues

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UNEP is the environmental consciousness of the United Nations System. It is not an implementing agency. Research and application of knowledge is the responsibility of the specialized agencies and for governments. UNEP's role is to identify environmental concerns, assess the nature and scale of the problem, and as necessary, to develop and recommend methods or guidelines for the sound environmental management of the issue concerned. It does so by means of coordination and catalysis:

- Coordination of global activities and research to ensure the accurate analysis and efficient management of the issues

- Catalysis in the sense of encouraging and supporting relevant activities necessary to achieve the goal of managing the issue through avoidance, prevention, or mitigation of the problem.

UNEP draws the attention of the world to environmental issues and may make suggestions that specific issues be addressed. The decisions regarding what will be done are those of the UNEP Governing Council, a representation of member states of the United Nations. The Executive Director of UNEP has the responsibility to satisfy these decisions, and my task, as UNEP's atmospheric specialist, is to ensure that the appropriate assessment of relevant atmospheric issues is made in a timely and efficient manner upon which managerial decisions can be based. Thus the classic role of UNEP is problem recognition, assessment, and then identification of policy alternatives. UNEP is currently applying this policy to two major global issues - the risks to the ozone layer and the greenhouse gas/climate change issue.

Some may view this report as a collection of research results and information on the impacts of modification of climate or the ozone shield. I am obliged to look at it in the broader context of future global response to environmental concerns and in particular how this report and the conference aid me in making available to governments the best assessment of ozone-layer

modification, its impacts, and the implications of climate change, in order that the most appropriate response can be formulated and applied. This report is to me a single link, yet an absolutely essential one in the protection of the ozone layer and in dealing with a future climate never before experienced by mankind.

To illustrate this, I would like to describe the events, these other links in the chain, that have led us to this point and to speculate what we can hope to achieve.

The hypothesis of Rowland and Molena of stratospheric ozone layer made in 1974 led to worldwide speculation and the categorization of the issue by UNEP as an emerging environmental issue. The UNEP Governing Council asked the Executive Director to convene an international conference to review the matter and my association with the Programme began when I was seconded from the national meteorological service for whom I worked to organize the conference, which took place at the State Department building in Washington, D.C. in March 1977. The outcome, as discussed by Golubev (this volume), was a World Plan of Action on the Ozone Layer requiring research carried out or coordinated by the appropriate specialized agencies and government and nongovernment institutions under the overall coordination of UNEP. The initial task was to assess the issue and quantify the risk preliminary to determining the response.

A Coordinating Committee (about twenty active members, mostly government representatives) meets regularly to consider recent research results and assess ozone layer modification and its impact. Under the plan of action, this assessment should consider the results of monitoring and modelling changes of the atmosphere, and should estimate the consequences for humanity and the environment of predicted ozone layer change, including UV-B radiation effects on human health, on aquatic and terrestrial ecosystems, on plants and agriculture, on climate and on the socioeconomic implications of such changes or of mitigation strategies, a menu similar to this report's table of contents.

The Committee first met in Geneva in November 1977 and has met eight times through June 1986. Each year its assessment has grown physically larger as knowledge improves; this year it incorporates the results of the NASA assessment made by an international team over the previous year. As a consequence of having to digest this voluminous product, it was not possible to make an assessment of effects of ozone layer change and, also as a result of the NASA effort in addressing the physical and chemical science of the ozone layer, an imbalance in the quality of the respective parts of the assessment became apparent. Effects science needed a boost and I decided on the need for a scientific conference on effects to inject momentum into the process to estimation of effects. By happy coincidence, EPA was travelling the same road, and we have combined forces to produce this report and the associated conference. My next job is to use the information presented here and with the help of the Coordinating Committee on the Ozone Layer (CCOL), make an assessment of effects to complement the already available physical assessment.

UNEP, in response to governments' requests, also organized workshops that will, among other matters, assess the costs of some of the possible measures

suggested to protect the ozone layer. Thus the World Plan of Action on the Ozone Layer is being implemented and the assessments made are the best possible under the circumstances.

Nevertheless, the issue is not one that can yet be confirmed by monitoring nor quantified with certainty by research. Unfortunately, it is not possible to await these clarifications and still have time to avoid the consequences of inaction. UNEP has been obliged at its Council's request to begin the process of identifying management options for the issue.

The Vienna Convention is now a reality and will soon enter into force. Soon an ad hoc legal and technical working group will be convened to decide on a very significant document, a protocol to the Convention on Chlorofluorocarbons, which will require its signatories to restrict their emissions of CFCs to agreed limits. Observance of these limits is likely to exact economic penalties and should not be overly conservative. UNEP's Environmental Law Unit will convene and service these meetings. My responsibility will be to provide the best available scientific and technical information, a globally accepted assessment of ozone layer modification, impacts of such modification, and a socioeconomic analysis of the consequences of changes and control. The program that I have outlined hopefully provides the lawyers and administrators sufficient factual data and realistic projections on which they can make realistic policy recommendations. The report and the "Effects Conference" have been essential to that process.

The option under consideration limits production and emission of CFC 11 and 12 as an initial step. Control of other CFCs and additional potential ozone-depleting substances are options available in the future, and will depend on progress in developing safer substitutes or technological improvements in manufacture and use of these chemicals to prevent emissions. UNEP will have a continuing role as assessment coordinator and will act, at least temporarily, as secretariat to the Convention.

The environment should not be manipulated beyond its capacity to return to its former state. Unhappily, the limit has been exceeded beyond recall in many instances, and economic demands oblige acceptance of change for the greater good.

Climate change is also under consideration by UNEP as a result of tropospheric trace gas increases, particularly carbon dioxide, and the discussions on potential impacts have been most useful. The UNEP program in this area mirrors that addressing the ozone layer problem: identification, assessment, and analysis of policy options.

Two assessments have been made and a consensus has been reached on the probable physical response. However, the problem of response is far more complex than for ozone. Prohibition of nonessential uses of relatively small amounts of some chemicals is one thing, limiting emissions of carbon dioxide from coal and oil burning processes is quite another. The 1985 assessment of the carbon dioxide/climate question at Villach provided the international community and, one hopes, governments with a broad program to follow. This includes a comprehensive menu of research needs and a requirement to undertake analysis of regional socioeconomic impacts of climate change. Our understanding of future regional climates is currently limited and a wide range of

possible as well as probable scenarios will have to be considered in the assessment process. UNEP will support a limited number of these regional exercises and will encourage governments to examine the consequences of climate change in their own regions. The methods for carrying out such policy exercises are under discussion. One can be sure a wide range will be considered. Some idea of the kind of thing that can be done is described by Parry (this volume) respecting the vulnerability of agriculture to climate variability and change in the climatic sensitive regions.

What UNEP would hope is that the large international effort will be closely coordinated and that the WMO/UNEP/ICSU Advisory Group on Greenhouse Gases established in response to a Villach recommendation can have a role to play. Only after considerable research and assessment will we be convinced that a global response is or is not necessary. The need for a climate convention is not as obvious as the need for a convention to protect the ozone layer. It remains an option that governments will have to consider, but presently we would urge them not to waste the time we have available for action, whether in cooperation with neighboring countries or by themselves, but to join in the policy analysis process.

THE POLICY CONTEXT

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This report is another important step toward understanding and recognizing the threats to human health and the world environment posed by ozone modification and climate change from a greenhouse warming. In a remarkably short period of time, an issue of concern to a small group of scientists has become an important policy problem as well. The focus of scientists and policymakers is no longer "whether", but "when", and with what effect. We have even begun to hear talk of the most difficult question of all: what can we do?

Consider what has been accomplished during the past 15 months:

- In March 1985, twenty countries signed the Vienna Convention for the Protection of the Ozone Layer, the first international agreement calling for action to prevent an environmental problem rather than simply respond to it.

- In October 1985, eighty scientists from twenty-nine countries met at Villach, Austria to assess our knowledge of the greenhouse problem. They concluded that the problem is not only real, but occurring much faster than had been thought, and recommended an "active collaboration" between scientists and policymakers.

- In January 1986, the National Aeronautics and Space Administration issued a report to Congress on processes controlling ozone, based on a two-year study by 150 scientists from around the world. While strictly a scientific study, the report warns that "we are conducting one giant experiment on a global scale by increasing the concentrations of trace gases in the atmosphere without knowing the environmental consequences."

- In the spring of 1986, the U.S. Department of Energy released four volumes summarizing our current understanding of the climate change issue. This effort also reflected extensive international scientific participation and peer review. The review of the global carbon cycle concludes with the recognition that "human effects on atmospheric composition and the size and operations of the terrestrial eco-systems represent major excursions that may yet overwhelm a life-support system crafted in nature over billions of years."

- On June 10 and 11, 1986, a Senate subcommittee chaired by Senator John Chafee held two days of hearings on the greenhouse and ozone issues. Unlike prior hearings on the subject, this one gave equal time to what can and ought to be done, as well as the status of scientific knowledge. Senator Chafee proposed six policy initiatives, and representatives of government agencies were pressed about their plans to address these problems.

Government officials, for the most part, have responded to this explosion of scientific concern with predictable and complacent calls for more research, but no action. For example, William Graham, the President's nominated science adviser, told the Senate hearing that "projections for the future have a large uncertainty to them and have to be reduced before we take actions." He suggested we need a "comprehensive understanding of the global environment," which might take a decade.

There is no denying the existence of major scientific uncertainties. However, I draw a conclusion opposite to Dr. Graham's. When dealing with risks that are grave but cumulative and irreversible, uncertainty is a strong argument <u>in favor</u> of action. We must take whatever steps are feasible as soon as possible to reduce the dangers. Inaction is not a neutral, low risk policy, but rather a gamble that risks much greater harm. As the Villach statement concludes, "While some warming of climate now appears inevitable due to past actions, the rate and degree of future warming could be profoundly affected by governmental policies on energy conservation, use of fossil fuels, and the emission of some greenhouse gases."

A wait-and-see approach also only makes sense if we can be certain that the changes will be gradual and detected in time to prevent catastrophe. The recent discovery of an "ozone hole" over the Antarctic in springtime demonstrates that natural systems can experience very rapid, marked changes almost before we have time to confirm our measurements. This phenomenon was not predicted and cannot be explained by the best available models; nevertheless, it happened over a period of less than a decade.

There are other negative consequences of delay. Some strategies, such as developing solar energy or air conditioning equipment that does not require CFCs, can only be implemented over a long period of time. Unless the development of these technologies is accelerated today, these options will not be available when rapid reductions in emissions become necessary.

The necessary policy responses will almost certainly become more severe as atmospheric concentrations increase. For example, we can limit long-term increases in the atmospheric concentration of CFCs by moderate action today, such as cutting aerosol uses and capping total production. Conversely, if

emissions are allowed to grow unchecked, future reductions will have to be much more abrupt, without the benefit of time to search for acceptable substitutes.

To allow the world's environment to deteriorate into a situation in which we are dependent on rapid and extreme responses is irresponsible. This "cure" may be as bad as the disease. As former EPA Administrator William Ruckelshaus (1984) has said, "The ultimate danger is that by remaining reliant on the 'catastrophe theory of planning' in an era producing catastrophes of a magnitude greater than in the past, we can place our institutions in situations where precipitate action is the sole option--and it is then that our institutions themselves can be imperilled and individual rights overrun."

It is also likely to take far longer to resolve the major scientific uncertainties than the decade suggested by Dr. Graham. In all likelihood we will experience major impacts before we fully understand them. The recent DOE assessment of the greenhouse problem, for example, concludes that it is impossible to predict when CO_2 induced changes will be identified with statistical confidence with greater precision than "over the next few decades." The problem, they warn, "may be too gradual to detect until it is well advanced, too advanced to stop by the time it is detected, and capable of inducing profound changes in the delicate environmental balances . . ."

The history of the ozone depletion issue reveals repeated assertions that further research will provide much better insights on the need for policy in three, five, or ten years time. When the designated period passed, the plea for "just a few more years" has been renewed. Since research constantly generates more questions, the process can be repeated many times.

Research will also not resolve the inherent and unavoidable uncertainty attributable to human behavior, the determinant of growth rates for CO_2, CFCs and quite likely an important factor in emissions of the remaining trace gases. The greatest uncertainty involved in predicting CO_2 emissions is the rate of growth in fossil fuel use, a variable that can be influenced by government policy, but not predicted through scientific research alone.

We must assume that many years will be needed to devise and implement effective international solutions to these problems. To avoid future political as well as environmental crises, we should adopt certain measures that are feasible now, recognizing that they will be only first steps. While multilateral and international cooperation will ultimately be required, this should not preclude short-term domestic action. The U.S. has a tradition of international environmental leadership, the best sources of scientific understanding, and the greatest resources. We can, and should be, a model for the world.

Several steps should be taken immediately, among them:

- An international effort to halt tropical deforestation, which accounts for a large share of CO_2 emissions attributable to biotic sources. Emissions from biotic sources are currently estimated to be equal to 20 to 40 percent of CO_2 emissions from fossil fuel use. A detailed program for large-scale planting and forest management is outlined in a recent report of the World Resources Institute, the World Bank, and

the United Nations Development Programme, Tropical Forests: A Call for Action. This program has received international support for many reasons, but it would also be highly beneficial from the standpoint of climate change.

- A ban on nonessential uses of CFCs and a production cap to limit future growth. There are proven, accepted substitutes for almost all aerosol uses of CFCs as demonstrated by the experience of the United States, Canada, and Sweden. There is also no reason to continue using CFCs for retail food packaging, whipped cream stabilizers, and other such uses. Greater use of recovery and recycling methods could reduce CFC use for solvents, foam blowing, and refrigeration and air conditioning. Over the next decade, we can redesign refrigeration equipment to operate on CFC-22 or other substitutes that present much less risk of ozone modification and climate change.

- An increase in energy efficiency. Numerous studies have shown opportunities for large reductions in the energy needed to power our cars, appliances, lighting, electric motors, and industrial processes. This could reduce our dependence on coal-generated electricity, producing substantial economic benefits while at the same time ameliorating the global acid rain problem. Such efficiency improvement would be of even greater benefit in the developing countries, where the cost of capital is greater and the infrastructure requirements for increasing coal production are enormous.

- Adoption of advanced technologies for producing electricity from natural gas. This could increase power supplies, lower costs, and reduce carbon dioxide emissions simultaneously. Technologies like advanced combined-cycle systems and steam-injected gas turbines are technically feasible, cheaper than coal, and environmentally superior in almost all respects. Substituting them for existing gas turbines would not increase our gas dependence and would significantly reduce the need for coal power.

- Tighter regulations to limit carbon monoxide emissions from automobiles. This would reduce a suspected indirect source of methane accumulation. Further reductions could also be attained by efforts to control leakage from gas pipelines and abandoned coal mines.

- Preparation of environmental impact statements on all projects that may contribute to or be affected by climate change and ozone modification, as recommended by Senator Chafee. This is not being done, although we believe it is legally required by the National Environmental Policy Act. The impact statement process is valuable because it expands awareness of the issue throughout the government and would help to identify further opportunities to prevent and adapt to climate change.

These steps can all be justified not only because they reduce the dangers of ozone modification and climate change but because they are environmentally sound. As the Villach statement notes, "Reduction of coal and oil use, and energy conservation undertaken to reduce acid deposition will also reduce concentrations of greenhouse gases; reduction in emissions of CFC will help

protect the ozone layer and will also slow the rate of climate change." Implemented today, they would substantially reduce the risks we face.

More aggressive action will be needed in the long run. We should seriously study carbon taxes to discourage future use of coal and shale and to finance reforestation, solar energy development, and energy efficiency technologies. We must begin the transition now or find ourselves increasingly dependent on fossil fuels for our prime source of energy.

International cooperation on these issues must be continued, building on the model of the Vienna Convention for the Protection of the Ozone Layer. China and the Soviet Union consume as much coal as the United States and currently plan to significantly increase their use. I strongly support Senator Chafee's proposal for high level government meetings on these issues, including the next US/USSR summit. It is also time to plan an international convention to respond to climate change. A convention could be a mechanism for developing common policy approaches as well as cooperation on scientific concerns.

It would also be a terrible mistake if these problems were viewed as primarily concerns of the industrialized countries. In the developing countries, increased use of fossil fuels and CFCs could largely offset reductions achieved elsewhere. Some developing countries, particularly those with populations concentrated in low lying coastal areas, would be among those to suffer most from the effects of climate change and ozone modification. A major focus of international efforts must therefore be to meet the legitimate needs of the developing countries for energy and refrigeration without greatly adding to the buildup of greenhouse gases.

Lest these proposals be viewed as opposition to further scientific efforts, I should emphasize my belief that increased research--particularly research on health and environmental effects--is also essential. This is so not only because we need to improve our knowledge of the risks we face, but also in order to allow preparations for changes that are now inevitable. Past emissions of trace gases may have already committed the world to an average warming of one degree or more, and therefore perhaps twice that in high latitudes. As a practical matter, we are committed to still more warming and climate change because of built-in momentum in our patterns of energy supply and use. It will take years to develop and implement emission control strategies and to replace the existing energy and industrial infrastructure.

Research on effects is also important to help define the risks of these problems in widely understood terms. A major reason for the extensive media interest in the Senate hearings was undoubtedly the detailed description of potential impacts from ozone modification and climate change. The public was told not only that global <u>average</u> temperatures could rise several degrees, but that the number of <u>Washington</u> days hotter than 100° could rise from 1 to 12 (see Hansen et al., this volume). Similarly, graphic terms were used to characterize the potential devastation of U.S. forests and shoreline development.

We must take on these problems as part of our responsibility to conserve and protect the community of life on the planet. Although our dominion over the earth may be nearly absolute, our right to exercise it is not. The

responsibility for the greenhouse and ozone problems is ours. As trustees of the earth for future generations, we must correct what we have wrought.

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The Need for Responsible CFC Policy

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I am honored to present my views on the issues confronting us as scientists, policy-makers, business representatives, interested participants, and most importantly, inhabitants of our earth. The tasks we perform in our efforts to better understand the effects of potential ozone depletion, global climate warming, and climate modification are important to all as we assess these issues.

They have received a great deal of attention lately as a result of the hearings held by Senator Chafee's Environmental Pollution Subcommittee. Unfortunately, the media accounts of those hearings could not explain the enormous scientific complexities and uncertainties surrounding the ozone depletion and climate change issues. The scientific uncertainties of these issues are difficult for the general public to comprehend and they cannot be adequately conveyed on thirty seconds of network news coverage or a brief news article.

Hearings such as these are useful if they help us to remain alert and responsive to the issues and the policy questions they engender; if they serve to inform, not to alarm; and if they promote rational discourse and action, rather than responses based on emotion.

It is critical, therefore, that these meetings are held and that reports such as this are generated to ensure the development of international scientific consensus on these important issues.

Much has been made of the statement from the National Aeronautics and Space Administration (NASA)/World Meteorological Organization (WMO) Science Assessment that we're conducting an experiment "on a global scale by increasing the concentrations of trace gases in the atmosphere." Evolutionary history tells us that the composition of the global atmosphere has naturally been in a dynamic state. The significant difference between the human race

today and our evolutionary predecessors is that today society has the capability to change the earth's atmosphere and also has some ability, albeit limited, to understand the consequences of our actions and to try to avoid any adverse effects of our so-called "experiment."

It is somehow ironic that the same capacity that allowed us to have an Industrial Revolution, to develop new technologies, and to land men on the moon, now leads us into the maze of complex questions we must now address.

Such is the case with the development of chlorofluorocarbons, or CFCs as they are commonly known. These synthetic compounds were first developed in 1931 as a result of an intensive research effort to identify an efficient, safe refrigerant for home use. Since that time they have come to be used in a wide variety of applications besides refrigeration, most notably for air-conditioning, foam product manufacturing, cleaning solvent for the electronics industry, and many other applications. Their uses have become so widespread because of their many desirable properties. They are nonflammable, noncarcinogenic, noncorrosive, extremely energy efficient, and they have low toxicity.

The contribution of these substances to worker safety and consumer health is substantial considering the products in which they are utilized and the contribution of such products to our quality of life. It is incumbent on us, however, to examine these substances and their potential for harming the environment in the long run. On the other hand, we should not rush into short-term regulatory decisions that result in the use of alternatives that present immediate, real threats to worker and consumer safety with little or no environmental benefit. In this case, it appears that the penalties of premature regulation could be real in terms of an immediate increase in exposure to more toxic substances or increased energy consumption.

We must not forget that other substances also have the potential to modify the ozone layer and to increase the earth's average surface temperature. Even if CFCs had never been discovered, these two issues would still be with us today.

The Alliance for Responsible CFC Policy dismisses the notion of "wait and see" on the ozone depletion and climate change issues as unacceptable. I would hardly characterize the activities over the last twelve years as "wait and see."

The United States and many other countries developed scientific programs to understand the ozone layer and the processes that control it. Practically all we know about the stratosphere has been learned in the last ten to fifteen years. Furthermore, intensive programs to study climate and possible climate modification are continuing. In addition, U.S. industry strongly supported efforts to develop the international framework for addressing the ozone depletion issues through the Vienna Convention for Protection of the Ozone Layer. Given the enormous complexities of the issues we are confronting, I believe that the progress from the scientific and policy development perspectives has been remarkable.

In our view, these global issues can only be addressed at the international level. Further unilateral actions by individual countries would provide no significant environmental benefit. To this end, the progress made

to date on international scientific and policy consensus is substantial but much remains to be done. The science, as we currently understand it, tells us, however, that there is additional time in which to solidify international consensus. This must be done through discussion and negotiation, not through further unilateral regulation in the name of "leadership." Experience tells us that other countries do not regulate simply because the United States does. In fact, the opposite may be true. Other nations may view our unilateral actions as solving the problem; thus, giving them reason to do nothing.

We are not saying, however, that industry should not take precautionary measures while the research and negotiations continue at the international level. As Chairman of the CFC Alliance, and as the Chief Operating Officer for a major air-conditioning manufacturer, I believe we can, we have, and we will continue to examine and adopt such prudent precautionary measures, including:

- Recapturing, recycling, and recovery techniques, where cost-effective, during manufacturing processes to control CFC emissions

- Efforts to transition to existing alternative fluorocarbons that are considered to be more environmentally acceptable

- Equipment change-out practices to replace, where possible, existing systems at the expiration of their useful life to equipment utilizing other CFC formulations

- Technical practices in the field to prevent CFC emissions where practical

- Encouragement of CFC users to continue to look for technologies, processes, or substances that are as efficient, safe, productive, or better than what is presently available.

I believe such actions respond to the concerns raised by the issues discussed at the International Conference on the Effects of Ozone Modification and Climate Change. I know, for example, that many of these practices have been put into effect already. For example, unitary air-conditioning equipment has converted substantially over the last twenty years to R-22 from R-12. Many manufacturers have instituted recycling and recapturing techniques in their plants. But as the history of humanity has shown, we are always striving to improve. What we must guard against is a solution that could be viewed as a step backwards. Many of the CFC uses have no technically feasible alternative CFC formulations. Other substances discussed as substitutes for CFCs, including sulfur dioxide, ammonia, and methyl chloride raise immediate concerns for environmental safety, and worker and consumer protection.

The using and producing industries of the CFC Alliance are committed to being active participants in the exploration and the successful resolution of these issues. We would like to think that the reasons our companies succeed are because the products we offer contribute to the quality of life for us all, and we hope to continue to do so in a responsible fashion.

The potential effects discussed in this report are serious. Through continued pursuit of scientific research relating to ozone depletion and climate change we can understand the nature and extent of any effects that may actually occur and how we can best deal with them. I also hope that prudent and responsible actions on the part of government, the private sector, and industry will minimize any deletorious impacts on society as a result of premature or unwise regulatory decisions.

As I indicated above, we have established the framework of an international plan to address these important environmental concerns. These environmental concerns are serious, but their successful resolution will require greater global cooperation in conducting the necessary scientific research and monitoring, and in developing coordinated, effective, and equitable policy decisions for all nations.

Cooling the Chemical Summer: Some Policy Responses to Ozone-Destroying and Greenhouse Gases

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This exciting report has produced the most comprehensive international exchange of knowledge ever seen on the known and potential consequences of unabated release of ozone-destroying and greenhouse gases. We will not attempt to summarize the papers or discussion, except to say that the picture of our future being painted by the world's best scientific minds is, to use the word without exaggeration, disastrous. Unless the private and public institutions of the world respond, we can look forward to steady increases in UV-B radiation due to ozone-destroying gases, including CFCs, halons, and other compounds. Indeed, Watson (this volume) reports that 2 to 3 percent ozone depletion may already have been observed, taking into account the contribution of atmospheric aerosols. As a consequence, we can expect increases in fatal and nonfatal skin cancer; broad, systemic disruption of human immune responses; cataracts and other vision disorders; and possibly many other illnesses. We can expect many serious environmental harms from the increased UV-B, including widespread damage to crops and natural vegetation (Teramura, this volume), possible disruption of microbial populations on which the terrestrial ecology depends, and possible disruption of critical aquatic food chains (Worrest, this volume). We can expect a certain amount of climate change solely from the redistribution and overall loss of ozone.

From the greenhouse gases--carbon dioxide, methane, nitrous oxide, CFCs, and others--we can expect a steady global warming to temperatures that even within a decade may exceed the range experienced in the last one hundred thousand years. The warming promises major consequences for rainfall and other weather patterns (Manabe, this volume) and a sharply higher sea level (Titus, this volume). Agricultural and forest belts are likely to shift, possibly by hundreds of miles (Parry, this volume). Even the major currents and circulation patterns of the ocean may change; northern Europe may plunge into cold even as the world as a whole heats up. The direct and indirect health effects of the warming are likely to be massive, ranging from large increases in summertime urban death-rates to death and disease brought about by drought, storm, and flood.

These catastrophic prospects should bring home to governments and ordinary citizens the simple concept that the atmosphere and climate are fragile. The only thing objectively good about the current atmosphere and climate is that they are the ones we are used to. Life and civilization are adapted to this environment; change necessarily will be disruptive. Especially because so much of the world's population lives with but a small agricultural and economic safety margin, almost any stratospheric or climatic change will be for the worse.

Yet, except in parts of the world where the weather is traditionally variable and where life is lived close to the margin, most governments and most people take the stability of climate for granted. The common conception, to this point, has been of an atmosphere resilient enough to absorb stresses of human origin without danger to existing ecosystems and the economies which depend on them. Even more dangerous is the Panglossian view, encountered in some governmental quarters, that greater radiation and heat will be good for life on earth. These illusions must be rapidly dispelled.

Senate hearings held in June 1986 on the greenhouse effect and threats to the stratosphere went a long way to dispel these illusions in this country and to awaken our public and political system. It is hoped that the participant in this international conference will carry the same message to his or her country. The message, however, requires persistent repeating by scientists, governmental officials, nongovernmental organizations, and ordinary citizens around the world.

To be sure, much of the scientific data is incomplete. Yet the tip of the iceberg which is visible argues strongly for changing course now. As EPA Administrator Lee Thomas recognized in his Senate testimony and in this volume, with the health and environmental stakes so high, the world cannot afford the luxury of waiting for certainty. In fact, with the stakes so high, uncertainty is an even more powerful argument for taking early action. How many unexpected surprises, like the Antarctic ozone hole, can the world afford to risk? The appropriate standard of proof for this problem is aptly captured in the American Clean Air Act, which requires action to protect the stratosphere when damage to it, and damage to health and welfare down below, "may reasonably be anticipated."

Even though some degree of warming and ozone destruction are now inevitable, the future extent of the damage is dependent on decisions to be made in the coming few years. The magnitude and timing of these changes are fully under human control.

In this country, it is most encouraging to see the keen awareness and interest of key legislative leaders such as Senators Chafee and Gore, who were joined in the landmark hearings by Senators Stafford, Mitchell, Baucus, and others. We are also encouraged, thus far, by EPA's conduct of the scientific assessment and decision-making process pursuant to the Stratospheric Ozone Protection Plan, of which this conference is a part, and by preparations for resumption of CFC protocol negotiations next fall.

Senators Chafee and Gore have laid out a number of important, positive policy initiatives which NRDC strongly supports. This report has demonstrated to us, however, that an even stronger policy response is required by the

magnitude of the threat to global health and welfare. Our purpose in the remainder of this paper is to set forth some additional, though surely incomplete, proposals on CFCs and CO_2.

CFCs: SHARP REDUCTIONS ARE NECESSARY

CFCs are the dominant chemicals in ozone depletion. They also account for at least one sixth of the current atmospheric stock of anthropogenic greenhouse gases, and they are growing more rapidly than others.

Domestic and international discussion has focused up to this point on alternatives for CFC controls which range from very modest measures to, at most, a cap on production at current levels. But there are now compelling reasons to conclude that it is no longer sufficient to talk just about avoiding increases in CFC production. Even with such a cap, CFC levels in the stratosphere will continue to increase. Given the gravity of both problems and the relative difficulty of rapidly affecting emissions of other gases, CFC reductions clearly present the best present opportunity to stave off ozone depletion and to limit the global warming.

Consequently, NRDC supports actual, rapid reductions in production of CFCs and related chemicals. We offer the outlines of such a proposal here, acknowledging that many details need to be developed. We propose, both for domestic regulation and international agreement, an 80 percent cut in permissible production of CFC_{11}, CFC_{12}, halons, and perhaps other compounds, over the next five years, and a total phaseout over the next ten years.

We would exclude from these production limits substances such as CFC_{123} and CFC_{134A}. These are promising alternatives for air conditioning and refrigeration. They are safer, at least from a stratospheric ozone perspective, because they break down in the troposphere. At this point we are not sure how to treat CFC_{22}, which could be substituted in mobile air conditioning. It is also an ozone depleter, but at a lower rate than CFC_{12}. Much will depend on whether CFC_{123} or CFC_{134A} become adequate substitutes and on whether the world requires mobile air conditioning at all.

In this connection it was most distressing to hear the major domestic producers of CFCs state, at the March 1986 workshop and subsequently, that in the early 1980s they essentially stopped product development and toxicological testing on potential alternatives to CFC_{11} and CFC_{12}. Even so, currently available information indicates that CFC_{123} and CFC_{134A} can be readily developed into feasible alternatives. American industry representatives to the recent Rome meeting are reported to have said that they can produce these compounds for three to six times the amount of CFC_{11} and CFC_{12}. The cost should drop off with volume and time; but even if it did not, it still would amount to less than a $10 rise in the price of a refrigerator. It is also most distressing, given the industry's prior opposition to projections that CFC production will grow, to read that the major American company, DuPont, is planning to expand production of CFCs in Japan.

We recommend consideration of proposals to give credits against these production limits for uses from which producers can prove, to domestic and international authorities, that no emissions result. Such an approach would encourage closed systems and product recovery and recycling. Any such system

of exceptions, however, would have to be based on rigorous demonstrations, with the burden of proof strongly on the producer.

A market-oriented phaseout should be supplemented with a ban on specific frivolous uses. In the United States, substantial strides have been taken to eliminate non-essential aerosol uses. But even here certain absurdities are still cherished. We ought to be able to reach reasonably quick agreement that the modest virtues of using CFC_{115} as a whipped topping stabilizer or CFC_{12} in chewing gum remover, boat horns, and pressurized drain cleaners should give way to protection of the atmosphere and climate.

A phase-out over this period would allow time for an orderly transition to other chemicals, other processes, and other end-products. The gravity of the situation demands nothing less. Cuts of this magnitude will not even prevent increases in the level of ozone-destroying CFCs reaching the stratosphere; that appears to require an 80 percent cut in today's CFC production, not production five years from now.

CO_2: THE NEED TO LIVE WITHIN BUDGETS

We do not pretend to comprehensively address strategies for CO_2 control in this paper. We want to emphasize, however, the enormous opportunity to stabilize or even cut CO_2 emissions from industrialized nations' electric power generation through conservation and efficiency improvements. We have borrowed heavily here from the work of our colleagues Ralph Cavanaugh and David Goldstein in NRDC's San Francisco office. Here are some startling statistics they have compiled:

- The typical American office building is lit by electric lights that consume six to nine kilowatts of electricity per square foot per year. Commercially available state-of-the-art technology can reduce consumption to 1.5 kilowatt hours per square foot without sacrificing reading ability or other functions of lighting.

- Typical residential water heaters use 4500-6000 kilowatt hours of electricity per year; state-of-the-art technology only uses 800-1200 kilowatt hours per year.

The National Resources Defense Council estimates that American residential and commercial electricity use can be cut in half through efficiency improvements such as these. NRDC estimates that industrial electricity use could be cut by 25 percent through conservation and efficiency improvements. In California and in the Pacific Northwest, utilities have invested more than half a billion dollars in residential efficiency improvements, i.e., buying efficient refrigerators instead of building new power plants. These efficiency investments, moreover, are clearly cheaper. Measures such as these, applied nationwide, could substantially trim projected CO_2 emissions.

On the basis of this potential, we wish to offer the outlines of a modest proposal for establishing "CO_2 budgets" for the utilities and industries of the United States. For a start, Congress should enact legislation requiring each utility to develop scenarios for alternative CO_2 futures, in conjunction with state regulatory authorities, EPA, and other agencies, through an open, objective public process. These scenarios should include low- and no-CO_2

growth futures, and they should place primary reliance on efficiency improvements and alternative energy sources, without increased dependence on nuclear power. Similar efficiency analyses should be required for major energy-consuming industries, including the transportation sector. Once the opportunities for saving energy through attractive conservation and efficiency investments are apparent, we will be able to take concrete steps toward reducing emissions of CO_2 and the global warming that results.

CONCLUSIONS

We have no illusions that these proposals on CFCs and CO_2 are either fully developed or sufficient alone. But as Senator Gore (this volume) suggests, the institutions of government, science, business, and other sectors must not be paralyzed by the enormity of the total problem. Rather, we must break the problem down and come to grips with as many of the pieces as possible, as fast as we can. Even if significant stratospheric and climatic change still results, our efforts will be justified, for surely we will know that without them, things would be even worse.

Climate Change and Stratospheric Ozone Depletion: Need for More Than the Current Minimalist Response

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Devotees of late night television in the United States may have seen the celebrated W.R. Grace and Company deficit trial advertisements. An elderly man, presumably of our generation, is on trial for failing to halt the mushrooming federal deficit. This courtroom scene in the year 2017 has the defendant facing a jury of children and an adolescent prosecutor who asks, "In 1986 the national debt reached $2 trillion. Didn't that frighten you?" Our contemporary lamely replies, "No one was willing to make the sacrifice." Stepping down from the witness stand, he implores, "Are you ever going to forgive us?"

While this advertisement may be too strong for the sensibilities of the television networks, it may be an accurate representation of how our grandchildren will view our mortgaging the future of the global environment. By 2017 our grandchildren will be struggling with a radically warming world climate causing environmental changes beyond anything ever witnessed by our species. Unless humanity profoundly alters energy consumption and emission practices, the global environmental trauma could become the ecological equivalent of the hyperinflation in Weimar Germany in the 1920s, with perhaps as profound consequences for the health of democratic government.

Mid-range projections of average global surface temperature warming by 2100 are generally at or above 5°C. Virtually all plausible energy-use projections (other than those hypothesizing the destruction of humanity in a final world war) point toward a doubling of the preindustrial levels of carbon dioxide well before the end of the twenty-first century. We are told by an eminent climatologist that this CO_2 doubling alone would warm the earth by an average of 3°C. As a result of recent calculations in some of the more

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[1]The author served from September 1983 through January 1986 as Staff Director of the Office of Air and Radiation of the U.S. Environmental Protection Agency.

sophisticated climate models of various feedback effects associated with a CO_2 doubling, the likely warming due to such growth of carbon dioxide in the atmosphere may prove to be at least 4°C (Hansen, this volume).

Although fossil fuel burning alone could produce a doubling of preindustrial CO_2 levels in the next seventy-five years, such a doubling could be accelerated by a decade or more if we continue to clear the world's forests at current rates. The biosphere, especially forests, constitutes a major sink for taking up carbon dioxide so that it does not build up in the atmosphere. Yet the largest source of such uptake, the tropical rain forests, is often severely pressed by development pressures in Third World countries from both indigenous sources and multi-national companies.

Despite abundant evidence that the buildup of carbon dioxide levels alone could produce an average global climate warming of 5°C by 2100, the most plausible current projections indicate that this CO_2-induced temperature warming will be roughly matched by a temperature rise due to a simultaneous buildup in other trace gases as chlorofluorocarbons, carbon tetrachloride, nitrous oxide, carbon monoxide, methane, and compounds of bromine.

The long-term implications of such a rapid climate warming for humanity and most other animal and plant species on this planet are staggering. These involve losing tens of millions of acres of coastal land to the sea, the impairment of many of the world's port facilities, the loss of countless lives of coastal and lowland dwellers to increasingly destructive storm surges, and massive salt water intrusion on fresh water supplies. The greatest human toll is likely to come in famines that could ultimately claim the lives of hundreds of millions in Third World countries. The tragic famine we are now witnessing in Africa may be but a small harbinger of the catastrophe that will unfold as desertification claims arable land and shifts in rainfall patterns disrupt already marginal food production and distribution systems. Although many plants will grow more rapidly in a higher CO_2 environment, it is unlikely over the next century that such potential gains in the food supply would match the losses caused by migration of food belts. Moreover, the non-CO_2 greenhouse gases provide no such benefits but could disrupt the climate just as much.

Besides its potentially large toll in human lives, this rapid climate change will probably destroy the habitats of thousands of animal and plant species, thus robbing our planet of much of its biological diversity. In addition to its direct human and ecological toll, adjustments to this rapid climate change could be expected to consume the entire growth dividend humanity would have used to improve living standards of future generations and to redress the impoverishment of the Third World. Huge sums would be required for dikes to preserve many coastal areas, and much of our planet's great investment in agriculture would be made obsolete by a rapid change in climate.

As apocalyptic as the consequences of such climate shock would appear to be over the long haul, people tend to glaze over at discussions that seem more relevant to their great grandchildren. Economists have developed the concept of discounting the value of human lives saved in the future. As some have pointed out, by adopting a high enough discount rate, one could conclude that the destruction of human civilization one or two centuries from now is of little or no economic consequence in present value terms, even if such a certain fate results from today's decisions. Sadly the calculations of most

public policy-makers seem equally unmindful of the injunction of that great political philosopher Edmund Burke that government owes a duty not only to the living, but also to the dead and to those who are yet to be born.

Yet, as some eminent NASA scientists have recently projected, climate change is no longer merely a concern for future generations. By 1990, they suggest, we are likely to see temperature changes outside of the normal range of variation with an increase of about 1°C in average global surface temperature between now and the year 2000. At the end of this century humanity could face a warmer world than at any time in the last hundred thousand years with the prospect of a continued warming at an ever-accelerating rate.

A major factor in the acceleration of these climate warming projections has been a late-blooming recognition of the important role of highly absorptive greenhouse gases, such as chlorofluorocarbons, carbon tetrachloride, and various bromine compounds, which remain in the atmosphere for decades if not centuries before breaking down. Methane growth due to agriculture, and nitrous oxide and carbon monoxide growth from fuel combustion have also caused the warming projections to rise.

Because of their powerful bonding and insulating qualities, chlorofluorocarbons are being used for a profusion of uses well past refrigeration and air conditioning to such diverse purposes as computer manufacturing and preserving the taste of a "McDLT" sandwich from a fast-food restaurant. These same qualities that make chlorofluorocarbons such readily adaptable commercial compounds also make them powerful greenhouse gases and effective depleters of our stratospheric ozone layer.

Due to the rapid growth in CFC use during the 1980s and the rapid buildup of bromine compounds, the danger to the stratospheric ozone layer appears greater than was originally thought when concern first arose in the mid-1970s. Yet much more important than the sizable increases in skin cancer, potential weakening of the human immune system, and likely crop and materials damage resulting from a chlorine and bromine compound induced depletion of the stratospheric ozone layer are the sizable boosts that such gases will provide to climate warming.

Given present CFC-use projections, it is conceivable that these compounds alone will produce an amplification of 1° to 1.5° C in the total global temperature warming over the next several generations. A small increment in the greenhouse warming can also be anticipated from the growth of such chlorine compounds as carbon tetrachloride and methyl chloroform as well as by a profusion of bromine compounds.

These stratospheric perturbants would be the first targets of any effective international effort to slow the greenhouse warming. They are all industrially-produced compounds, many virtually unknown two generations ago. Many have some available substitutes, which are neither stratospheric perturbants nor greenhouse gases for most commercial applications. Regulation of these compounds could afford dual benefits by providing stratospheric protection and slowing the greenhouse warming. Control of even small volumes of

these chlorine and bromine compounds can have a highly beneficial effect, due to their long persistence in the atmosphere and their tremendous absorptive potential (sometimes several thousand times an equivalent molecule of carbon dioxide).

Any effective U.S. and international effort to address the dual problems of greenhouse warming and stratospheric ozone depletion will require a much more tangible commitment of resources and attention by senior policy-makers in the major industrial nations. In the United States there recently have been some encouraging indications of intellectual recognition by senior policy-makers of the importance of the problem of climate change. William Ruckelshaus' strong foreword to the provocative work Greenhouse Effect and Sea Level Rise (Barth and Titus 1984) and Lee Thomas' clarion call in March 1986 for stratospheric ozone protection pointed out the critical importance of these issues.

Yet recognition of these issues has not translated into a tangible resource commitment. Despite indications that prospective climate change dwarfs all other environmental problems combined, fewer than nine EPA employees out of a workforce of about 12,000 work full-time on either the issue of greenhouse warming or stratospheric ozone depletion. Although the proportion has grown considerably in the past year, still only about one-tenth of one percent of EPA's total resources is devoted to addressing these issues. This minimalist resource commitment is not due to a lack of will on the part of EPA's senior leadership but to the statutory ambiguity of EPA's role and the deep-seated hostility that the Office of Management and Budget (OMB) has exhibited toward EPA's addressing such first-order environmental issues as climate change, indoor air, and radon. OMB has resisted giving EPA resources in apparent fear that the agency might uncover problems with resulting budgetary or regulatory consequences. While somewhat greater sums have been directed at studying aspects of climate change at the National Aeronautics and Space Administration, the National Oceanographic and Atmospheric Administration, and the Department of Energy, no coherent federal-wide focus exists on these problems, which will ultimately affect virtually every agency in government.

With a few exceptions the resource commitment to seriously addressing these issues by U.S. environmental groups has been equally fainthearted. Some environmentalists, by reflexively opposing all forms of nuclear power, have helped increase our dependence on fossil fuels. Moreover, both greenhouse-induced warming and stratospheric ozone depletion are global problems, and environmental policy-makers and environmental organizations in other industrialized countries have often lagged behind those in the U.S. in addressing these problems.

Despite the clear inadequacy of the present response to the prospect of climate change, a number of tangible steps can be taken by the U.S. and other countries to make the problem more manageable. These include:

- Preservation of critical satellite tracking research and climate modeling concerning ozone depletion and greenhouse warming. The recent turmoil at NASA, the destruction at launch of a key weather satellite, and the general environment of federal budget austerity have placed some critical research in jeopardy. Its loss could

greatly hinder our developing a clear understanding of the likely pace and regional implications of climate change.

- Development of a serious external constituency for climatic stability including environmentalists, scientists, coastal dwellers, farmers, the nuclear and the solar industry, and others. If such coalitions are organized in the major industrial democracies, they can help to ensure the attainment of broadscale international agreements essential to responding to climate change.

- Immediate phasing out of such relatively frivolous and easily substitutable uses of CFCs as aerosols, egg cartons, and fast food containers through a combination of consumer boycotts, industry voluntary action, national regulation or taxes, and international agreement. Concerted activity by consumers to avoid CFC aerosols preceded U.S. regulatory action. A similar focus on the threat to the environment posed by such environmentally dangerous and frivolous uses of CFCs might trigger a similar scramble by fast food retailers to point out that their products are not only tastier, but safer for the environment, than those of their competitors.

- Approaching regulation of CFCs and other trace gases such as carbon tetrachloride, methyl chloroform, and bromine compounds by weighing their greenhouse absorptive potential, their residence time, and their ozone depleting capacity. Thus, even among CFCs, substitutions might be encouraged of longer residence time compounds by shorter residence time compounds.

- Where appropriate, amend environmental statutes to address possibly harmful substitution effects caused by proposed environmental regulations. EPA recently issued a notice of an intent to list perchloroethylene, a significant dry cleaning solvent, as a hazardous air pollutant under Section 112 of the Clean Air Act. Such listing and subsequent regulation could conceivably trigger a rapid movement in the dry cleaning industry to CFCs, on balance likely to pose much greater environmental dangers than perchloroethylene. Language specifically permitting consideration of greenhouse warming and ozone depleting effects of available substitutes would facilitate more rational regulation.

- Requirements that long-term projects reviewed under the National Environmental Policy Act consider climate change and sea level rise. This might be accomplished through amendment of implementing regulations or by a suit directed at an appropriate project, such as a coastal highway that has failed to consider likely sea level rise. Institutionalization of climate change considerations into the project planning process for long term public and private sector investments should ultimately save taxpayers and investors billions of dollars and ensure that we leave future generations a sounder environment.

- Insistence by bilateral and multilateral lending institutions that their funds not finance the destruction of tropical rain forests and other important global forest resources. Recognition of the global stake in preserving these resources, located largely in developing

countries, may ultimately require the industrialized countries to finance some of the economic loss developing countries would perceive occurring should they forego development in the tropical rain forests.

- Recognition, even in the face of the tragedy at Chernobyl, that alongside energy conservation nuclear power remains the likely principal alternative to fossil fuel burning over the next generation or two. Besides strengthening the powers of the International Atomic Energy Agency to improve safety standards and ensure against diversion of nuclear materials to nonpeaceful uses, recapturing public confidence in the safety of nuclear power will require implementing environmentally sound radioactive waste policies. It is likely that environmental and energy considerations may militate toward large scale nuclear plant construction before the end of this century. Yet to meet deep public concerns about the safety of nuclear power may require the development of a new generation of technology that is relatively invulnerable to nuclear meltdown. Governments, environmental groups, and the nuclear power industry have a common interest in the success of such an effort. Simultaneous satisfaction of safety concerns and economic considerations will require very rigorous safety standards coupled with a virtual regulatory certainty that careful adherence to such standards will ensure expeditious licensing and avoid protracted litigation.

- Renewed international research focus on improving the efficiency of such alternative energy sources as solar power and perfection of such potential breakthrough technologies as hydrogen powered vehicles.

- A concerted public-private sector effort to mitigate the costs of climate change by adjusting land use and coastal development policies to allow for the prospect of increasing sea level rise, by encouraging the development of crops that can flourish under rapidly changing climatic conditions, by factoring climatic change and rising CO_2 levels into the strategic planning of industry, and by incorporating the prospect of a rapidly warming climate into calculations of utility peak load demand and necessary future capacity.

Due to the enormous momentum in the earth's climate system already present from our massive increase in fossil fuel burning and release of many manmade greenhouse gases, adaptation will be an essential part of our response. The sooner we incorporate climate change considerations into our societal planning the better our prospect will be for turning the greenhouse warming from an unprecedented catastrophe to merely an enormous societal challenge. Yet, even the best adaptation and mitigation strategy may be of little avail if present energy use and gas release trends remain unabated. Action by EPA and UNEP to sharply curtail emissions of the greenhouse gases at issue may afford us the time to fashion the more comprehensive response that will ultimately be required.

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The Implications of Health and Environmental Effects for Policy

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ABSTRACT

In approaching the question of whether the protection of stratospheric ozone requires the control of CFCs and/or other ozone-depleting agents, the U.S. Environmental Protection Agency (EPA) has divided the problem into a consideration of future emissions and atmospheric and health effects. The first workshop was devoted to the former topic. From that session it is clear that in the absence of policy action, CFC use will continue to grow in the future. While the papers presented provided a wide range of possible future CFC levels, it is important to emphasize that no credence can be given to zero growth assumptions for either long term production or emissions.

The various papers in this report focus on the consequences of failing to manage emissions of ozone-depleting substances. These environmental and health effects are the damages that can be avoided by controlling emissions. These impacts can be distributed into direct and indirect categories stemming from UV-B radiation or climate change. The effects documented involve primary production sectors such as agriculture and fisheries, as well as higher-order damages to human health, materials, and coastal property. Little of the research has generated information in sufficient detail to estimate dose-response relationships. However, when we compare our current knowledge against the information on effects available in the late 1970s, we can see that there has been substantial learning on this issue. Several of the papers presented a sufficient range of responses to allow a preliminary examination of the benefits of controlling emissions.

Two trajectories of ozone depletion in response to alternative scenarios of chlorofluorocarbon (CFC) and trace gas emissions were selected to represent the 'with' and 'without' action extremes. These depletion predictions formed the basis for predicting effects in the United States. Control action is simulated in the atmospheric model by holding emissions constant at 1980 levels which is broadly similar to a production capacity limit. The main

analysis focuses on nonmelanoma skin cancers and the damages to PVC. Indirect effects of increased UV-B radiation are illustrated by extrapolating photochemical oxidant production and its yield-reducing impacts on major crop commodities. The avoided damages from now until the year 2025 were estimated to be approximately 1.65 million cases of nonmelanoma skin cancer and approximately $7 million of PVC damage. Yield reductions due to increased ambient ozone would be significant for soybeans and cotton beginning in 2010. Numerous effects not quantified are described qualitatively.

To complete the analytical illustration of stratospheric ozone management, the focus naturally shifts to the estimation of the costs of control action. The changes in economic surplus associated with the position of a production cap were derived from existing research results. Average annual present value control costs were estimated to range from $196 million to $455 million, depending upon the ease of substitution of alternatives. Transition costs might also be substantial if policy action is implemented with little advance notice. The safety implications of the substitutes also were neglected. However, given the relative magnitude of benefits and cost, the prudent course would be to focus on the design of efficient and equitable management strategies for limiting CFC emissions.

Consequently, the current focus of research resources should be to assess consequences of possible policy choices. What are the effects of differences in policies, timing, and force? If we delay policy action, will it be more difficult in the future? Delay would not provide the needed stimulus for research into substitutes or reduced emission technologies. What are the opportunity costs of deferring control? To address these policy questions and deliver information to a rational policy process, we need to focus our research resources in the next year on the articulation of our uncertainty and its explicit incorporation into policy analysis. What are the consequences of being wrong and what is the least risky alternative? The real challenge is the design of policies to limit CFC emissions with associated monitoring and enforcement components that will protect the environment but allow all nations to share in the benefits of these chemicals.

INTRODUCTION

This report presents results of scientific analyses of various effects associated with changes in stratospheric ozone. This document and the conference on which it reports is one part of a process that started in the fall of 1985. In approaching the question of whether the protection of stratospheric ozone requires the control of CFCs and/or other ozone-depleting agents, the U.S. EPA has divided the problem into a consideration of economic and technical issues associated with emissions, and the resulting atmospheric and health effects. The process is designed to provide the best possible information on potential ozone-depleting substances, their quantities and uses now and in the future, and the consequences associated with depletion. In organizing this massive amount of information, economists divide it into the broad categories of benefits and costs. Using this framework, then, we can establish a correspondence between the various conferences and reports and the information that economists believe is useful for policy analysis.

In the fall of 1985, there was a World Meteorological Organization (WMO) Climate Conference convened "to provide governments around the world with the best scientific information currently available on whether any human activities represent a substantial threat to the ozone layer" (Watson 1986). The executive summary from the conference report succinctly concludes that:

> Given what we know about the ozone and trace gas-chemistry-climate problems we should recognize that we are conducting one giant experiment on a global scale by increasing the concentrations of trace gases in the atmosphere without knowing the environmental consequences. (Watson 1986)

The next set of workshops attempted to delimit the size of this experiment by assessing current and expected future demands for CFCs. The effects and efficiencies of existing control policies were also reviewed. In our benefit-cost language, this information would enable us to assess the costs of any control action. The international component of this process was concluded in a May 1986 meeting in Rome. While there were disagreements among the delegations about the precise future for CFC production, use, and emission, there was a consensus that annual growth in CFC demand would likely be above zero but less than five percent.

This report represents an articulation of our best understanding of the benefits associated with any decision concerning the management of stratospheric ozone. These effects are viewed as benefits because they represent the consequences that would be avoided by pursuing a particular alternative course of action. Clearly, the range of alternatives includes the possibility of doing nothing.

This paper highlights the process by establishing a correspondence between seemingly diverse activities; summarizes the information presented in this report within the context of that process; and previews the next step in the process, which will consider general control strategies. The paper is divided into several sections which focus on the general methodology, the estimation of costs associated with control action, the evaluation of the associated benefits, and the implications of this preliminary assessment for further research.

THE GENERAL APPROACH

Attributes of the Problem

Before elaborating on the economist's world view of policy analysis, it is important to briefly consider several salient aspects of the stratospheric ozone depletion problem. One of the most interesting, yet vexing, characteristics of the problem is its global nature. This attribute is important if we think of the problem as one of managing a global commons. No individual, firm, or nation can capture the benefits from reducing emissions. We cannot exclude others from enjoying the benefits from our emissions reductions even if they do not contribute. Consequently, no individual actor bears the full consequences of their decisions to emit or not. This condition creates an imperative for concerted global action.

The lengths of lags in the atmospheric system due to the very long residence times of these chemicals result in two additional attributes of concern. The first is irreversibility: if the earth's systems are being severely perturbed, what will the new equilibria be like? Can we ever regain the old? Will the simultaneous changes wrought by ozone depletion and climate change irrevocably alter the biosphere? Further, what are the implications for future generations? These long lags necessitate long planning horizons and drive us headlong into the question of intergenerational equity. What are the responsibilities of the present to the future? Mishan and Page (1982) have argued that we should adopt the view that:

> the means for future well-being (should) be at least as good as our own, thus focusing attention on the future condition of the resource base and its ultimate renewability and the portfolio of catastrophic risks that are passed from one generation to another.

As a current custodian of this planet, I believe that this is an appropriate vantage from which to review the information presented in this report.

General Framework

As indicated in the introduction, the general framework of organization for this paper draws from the policy process in which we are engaged. Economists view this process as one of assessing the benefits and costs associated with alternative courses of action. In each case, it is important to evaluate the effects of a policy with respect to a particular baseline. This necessity is imposed upon us because we wish to ascertain which changes can be ascribed to the action of the policy and because the problem involves chemical substances with extremely long lifetimes.

Costs. In the case of stratospheric ozone, costs will be the net economic effects on CFC producers, consumers, and the economy as a whole. These effects are expected to fall under several categories: surplus losses, efficiency losses, nonrecoverable resource cost, safety cost associated with alternatives, and administrative costs (Yarrow 1986). Of these, administrative and transition costs can be effectively assumed to be zero. Administrative cost should be small because the number of CFC producers is small. Transition cost would be expected to be a function of the timing of the policy action. If the policy intent and its implementation date are announced well in advance of the proposed action, firms producing CFCs should have the opportunity to alter their resource allocations. A commonly employed measure of economic welfare is the sum of economic surpluses. Graphically, using linear supply and demand functions we can illustrate several of these concepts (Figure 1). In this simplified example, consumers' surplus is represented by the area under the demand curve DD' above the equilibrium price p*. Because the supply curve is depicted as a horizontal line and producers' surplus is normally the area below the equilibrium price level but above the supply curve, producers' surplus is zero. For any proposed policy we can compute the change in economic welfare as the sum of consumers' and producers' surplus.

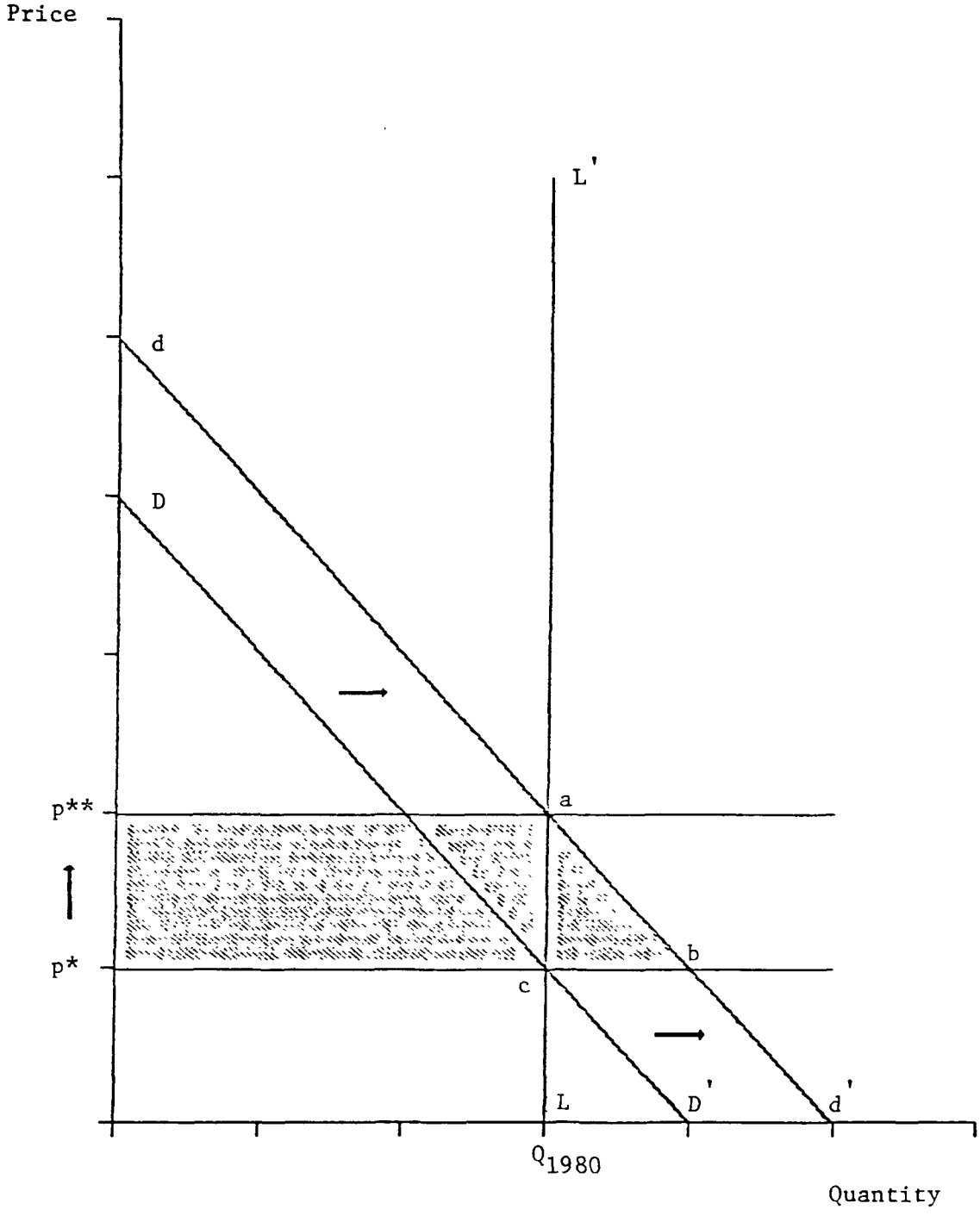

Figure 1. Conceptual Illustration Of Surplus Losses

To more effectively describe the approach pursued in this paper, it is necessary to consider the specific range of policies to be evaluated. Policies considered for the control of CFCs have either involved the prohibition of specific uses or limits on the total amounts that could be produced. Each policy type has its adherents and detractors. For expository purposes only, we evaluate a production capacity limit set at 1980 production levels. Because our intent is to summarize the large quantity of existing research on this topic into a useful integrated framework, the choice of policy for analysis was conditioned on the available literature (Palmer and Quinn 1980). Such a production capacity limit can be represented as a vertical line segment LL' set at the existing 1980 production level.

As demand for CFCs continues to grow, we would expect competition among users for the privilege of using some of the limited quantity of CFCs. This competition would likely take the form of increased prices for the chemicals. Such intensified competition is expected to result in the allocation of this limited supply to highly valued uses only. Thus, early in the adjustment process we would expect to see most aerosol applications of CFCs disappear due to their substantially increased cost. Figure 1 illustrates this process. Demand shifts to dd' but the quantity available cannot increase beyond the 1980 production level LL'. Depending on the feasibility of substitution in both technical and economic terms, CFC users will either switch to alternatives or compete for the limited supplies. The resulting change in economic surplus is measured as the shaded area p*p**abc in Figure 1.

Benefits. Noneconomists are often confused by the convention that the benefits associated with any environmental improvement are the damages avoided as a result of the policy action. We compute the production, use, and emissions of CFCs expected in the future in the absence of any policy action. These emission trajectories can then be transformed into estimates of ozone depletion over time through atmospheric models. The depletions are then translated into the effects that are addressed in the various volumes of this report. Similarly, a trajectory of emissions associated with the imposition of a production capacity limit can be calculated along with its expected effects. In real time, we would expect the time path of emissions to be altered in response to the effects of policy as indicated in the discussion of cost. Consequently, it is important to evaluate the behavioral adjustments of the economic actors prior to estimating the impacts of those decisions upon the atmosphere and environment. Thus we have a "without policy" set of effects and a "with policy" set; the differences between them represent the effects avoided. These are the benefits resulting from the policy action.

THE SPECIFIC ANALYSIS

Irrespective of whether we actually perform the benefit-cost computation and whether discounting is applied and in what degree, it is useful to identify the intertemporal distribution of benefits and cost. There are a number of theoretical and ethical issues associated with the application of discounting techniques across long time scales, and so it is important to take the intergenerational view alluded to earlier. The practical implication of such vantage is that most effects will be left in the physical units of occurrence.

As indicated in the preceding section, this type of analysis requires time dependent scenarios describing the evolution of the atmosphere in

response to emissions. This analysis utilized Scenarios A and C from the time-dependent, two-dimensional model presented by Stordal and Isaksen (this volume). Scenario A assumes that emissions of chlorocarbons will be held constant at 1980 levels. The specific chlorocarbon emissions considered are methyl chloride, carbon tetrachloride, methyl chloroform, F-11, F-12, F-22, and F-113. Detailed emission rates for the individual constituents are given in Table 2 of Stordal and Isaksen. Scenario A is assumed to approximate the effect of imposing a production limit at 1980 levels. This is an assumption since there is not a strict equivalence between production and emissions. For example, production could increase over time while emissions were held constant. This could be accomplished by reducing prompt emissions, improving recovery and recycling. However, this approximation is quite useful in allowing us to simulate the effects of the imposition of a production limit. The specific assumptions and effects associated with Scenario A, the "with action" alternative, are presented in Table 1.

Extension of the status quo, i.e., continued chlorocarbon production growth, is represented by Scenario C. Of the four time paths presented by Stordal and Isaksen, this is the most pessimistic in that it projects a high rate of sustained annual growth in emissions. While emissions do not necessarily correspond to production, this scenario was specifically derived from the late market maturation and new market development assumptions of Quinn et al (1980). These yield approximately a 4% annual rate of growth in production which was translated into a 2.7% annual increase in the rate of emissions of individual chemicals. An immediate question arises as to the realism of the production growth rate. From the UNEP review of CFC projections studies presented in Rome, 4% is an upper bound within the range of estimates produced. Thus, the results presented in this paper can be construed to be a conservative upper limit. It is conservative in the sense that no account is taken of the potential for demand increases among developing countries or among Eastern Bloc nations. This "without action" scenario is described in Table 2.

From the UNEP workshop on demand and controls held in Rome in May 1986, several facts clearly emerged. First, chlorofluorocarbons have highly desirable physical and chemical properties, which account for the wide array of beneficial applications in which they are found. These characteristics have resulted in substantial growth in demand and use. Despite the slump in sales induced by controls on aerosol applications in some countries in the late 1970s and a worldwide recession, production levels have increased beyond previous peaks. Projections of future CFC demand produced by a variety of alternative methodologies and authors all indicated that demand would grow. Major areas of uncertainty were identified as future population growth, the level of economic activity in the world, and the growth of sales in the developed countries. From that session it is clear that in the absence of policy action, CFC use will continue to grow in the future. While the papers presented provided a wide range of possible future CFC levels, it is important to emphasize that:

Table 1. Global Average Ozone Depletion With Constant Emissions at 1980 Levels

YEAR	PRODUCTION	EMISSIONS INDEX	OZONE DEPLETION
1980	constant	100	0.80%
1990	"	100	1.40%
2000	"	100	1.80%
2010	"	100	2.00%
2025	"	100	2.00%

Source: Stordal and Isaksen (this volume).

Table 2. Global Average Ozone Depletion With Continued Production Growth

YEAR	PRODUCTION	EMISSIONS INDEX	OZONE DEPLETION
1980		100	0.80%
	(growth of 4.0% per year)		
1990	"	155	1.80%
2000	"	227	3.00%
2010	"	299	4.40%
2025	"	421	7.50%

Source: Stordal and Isaksen (this volume).

> Under no circumstances do zero growth assumptions appear to be a reasonable basis for calculating long term emissions profiles. Moreover, growth rates in production and emissions of these chemicals will probably be higher in the next few decades than in the distant future. Holding other things constant, these findings will tend to increase expected ozone depletion relative to models with unrealistic steady state emissions at historical levels. (Quinn et al. 1980)

Further, it is important to remember that the results produced by Stordal and Isaksen were spatially, as well as temporally, distributed. In particular, their estimates indicate that ozone depletion will be latitudinally distributed with increased depletion at high latitudes. To illustrate the significance of these spatial differences, Tables 3 and 4 present the ozone depletion effects associated with Scenarios A and C, respectively, for 60°N latitude. Even with emissions held constant at 1980 levels, depletion is projected to reach 8% by 2025. If production and emissions continue to grow, 8% depletion would be attained at 60°N by 2000, rising to 17% in 2025. Consequently, the global average depletion trajectories employed in this analysis are conservative with respect to the extreme experiences that could result.

Costs

As previously indicated, the social cost of any control action can be expected to fall into several categories; but we only measure surplus losses. The costs of controlling emissions through the imposition of a production capacity limit set at 1980 levels are taken from a study conducted by Rand (Palmer and Quinn 1981). That study considered each of the major market outlets for chlorocarbon inputs with a focus on understanding both the availability and ease of substitution. In generic terms, the alternatives evaluated ranged from reduced input use from changes in product formulation or production technology, improved recycling and recovery, and switching to non-CFC inputs. For each major CFC user these alternatives were arrayed according to cost so that substitutions would occur in synchrony with increases in the price of CFCs. These responses were then aggregated for each chemical and for the industry as a whole.

There are three basic areas of uncertainty in this analysis: the speed of user responses, the rate at which new alternatives would be commercially provided, and the precise mechanism for market clearing. These uncertainties are accommodated by assessing the impact of these rates upon costs for various assumed rates. While the Rand study evaluated seven alternative scenarios, only two are considered in this paper. The extremes of the Rand results were selected to represent pessimistic and optimistic extremes that should bracket the actual costs. Their results were updated to 1984 terms to facilitate comparison. The annual cost of a 1980 production cap for the years 1981 through 1990 are displayed in Table 5. Using these annual estimates and converting to present value terms at an 11% discount rate results in cumulative control costs for this 10-year period ranging from approximately $1.9 to $4.5 billion. From Table 5, it is clear that costs would rise over time as the demand for CFCs continues to grow, as users continue to bid up the prices of the increasingly scarce chemicals, and as the easy substitutions are

Table 3. Ozone Depletion With Constant Emission at 1980 Levels at 60° North Latitude

YEAR	PRODUCTION	EMISSIONS INDEX	OZONE DEPLETION
1980	constant	100	2.40%
1990	"	100	4.50%
2000	"	100	6.00%
2010	"	100	7.00%
2025	"	100	7.90%

Source: Stordal and Isaksen (this volume).

Table 4. Ozone Depletion With Continued Production Growth at 60° North Latitude

YEAR	PRODUCTION	EMISSIONS INDEX	OZONE DEPLETION
1980		100	2.40%
	(growth of 4.0% per year)		
1990	"	155	5.00%
2000	"	227	7.90%
2010	"	299	11.50%
2025	"	421	17.00%

Source: Stordal and Isaksen (this volume).

Table 5. Time Stream of Costs

YEAR	OPTIMISTIC	PESSIMISTIC
	(millions of 1984 dollars)	
1981	27.4	49.2
1982	65.5	152.7
1093	135.7	317.2
1984	181.0	578.1
1985	285.2	873.2
1986	425.9	1427.6
1987	571.4	1453.2
1988	664.8	1480.9
1989	926.7	1511.0
1990	1543.5	1558.2
Present Value	1865.3	4543.0

Source: Palmer and Quinn.

achieved. In sum, for this period average annual control cost would be expected to range between $187 and $454 million.

Benefits

This report presents papers documenting effects upon human health and the environment from two problems that are linked through CFCs. Increased UV-B radiation throughout the biosphere is expected as the total ozone column is reduced through chain reactions in the stratosphere catalyzed by chlorine. CFCs are also radiatively active, absorbing infrared radiation and contributing to the climate warming due to the greenhouse effect. The direct and indirect effects induced by these changes are the damages associated with emissions and thus are the benefits that would result from controlling such emissions.

Historically, concern with ozone depletion has centered on increased UV-B radiation and its direct implications for human health. The effects documented include increased skin cancer, immune system suppression, and ocular damage. This paper focuses on the implications of skin cancer research for changes in human health when coupled with alternative trajectories of ozone depletion. Epidemiological studies conducted by the National Cancer Institute formed the basis for our effects assessment (Fears and Scotto 1983). Estimates of ozone depletion can be translated into increases in UV-B radiation through application of an enhancement ratio. In this paper that was assumed to be a conservative 1:2 (National Academy of Sciences 1984).

Coupling the alternative ozone depletion scenarios previously discussed with the enhancement ratio, trajectories of UV-B increase can be predicted. Using the results from the Fears and Scotto (1983) power model (more conservative than its exponential counterpart), UV-B increases are mapped into increased incidences of skin cancer. These UV-B increases are applied to the base case of 400,000 cases per year and adjusted according to the projections of a Caucasian population presented in Rundel and Nachtwey (1978).

Time and policy dependent rates and numbers of skin cancers for the United States are shown in Tables 6 and 7. Table 6 indicates that even with emissions held constant at 1980 levels, the number of new skin cancers would rise to approximately 142,000 per year by 2025. A more dramatic change is associated with growth in chlorocarbon emissions as the number of new cases for that year is estimated to be roughly 256,000 (Table 7). Our interest here is the difference between these trajectories, because that is the number of cases of skin cancer that could be saved by constraining chlorocarbon emissions and thus slowing the rate of ozone depletion. For example, about 114,000 cases of skin cancer could be prevented in 2025 by controlling chlorocarbon emissions growth. Table 8 presents this component of the benefits trajectory as the differences over time for each of the projection years. However, these results are more easily understood graphically. Figure 2 depicts the number of new cases of skin cancer expected if emissions are controlled (with action) and if emissions continue to grow (without action). The shaded area between these two trajectories is the total number of cases that would be avoided as a result of policy action. In this analysis, 1.66 million skin cancers could be prevented if emissions are controlled at 1980 levels. This result is all the more significant given recent reports citing the lack of progress in managing cancer and the need to emphasize prevention (Associated Press 1986). From this vantage, controlling chlorocarbon emissions would seem to be a judicious investment.

At a more mundane level, other direct effects of increased UV-B include materials damages, in particular impacts on polymers and elastomers. Andrady and Horst (Volume 2) identify effects ranging from discoloration to brittleness. The specific damage depends upon the type of plastic and its application. For example, in the case of rigid PVC used for home siding, UV-B causes discoloration which results in an increased rate of rejection. Increased PVC brittleness due to UV-B radiation in pipelines can cause premature failure and more serious consequences. In each case, these effects can be ameliorated by changing the plastic's formulation by adding titanium dioxide. Andrady and Horst (Volume 2) project the amounts of plastics expected to be used in the future, the increased UV-B this stock would be exposed to, and the costs of ameliorating the effects of such exposure.

Their results are interpolated for the two ozone depletion scenarios analyzed in this paper. Table 6 contains the damage estimates to U.S. PVC if emissions are controlled. At a maximum, these would be $8 million annually. In the absence of control, however, this figure would increase to $35 million per year (Table 7). Consequently, the maximum annual benefit in the form of foregone PVC damages would be $27 million (Table 8). Using a planning horizon extending to 2075 and applying a discount rate of 10 percent they estimate that the present value of PVC damages would range from $10 to $27 million depending upon the strength of PVC demand. While these damages are relatively small compared with the costs estimated for the production cap policy, they illustrate the pervasive nature of the effects of ozone depletion.

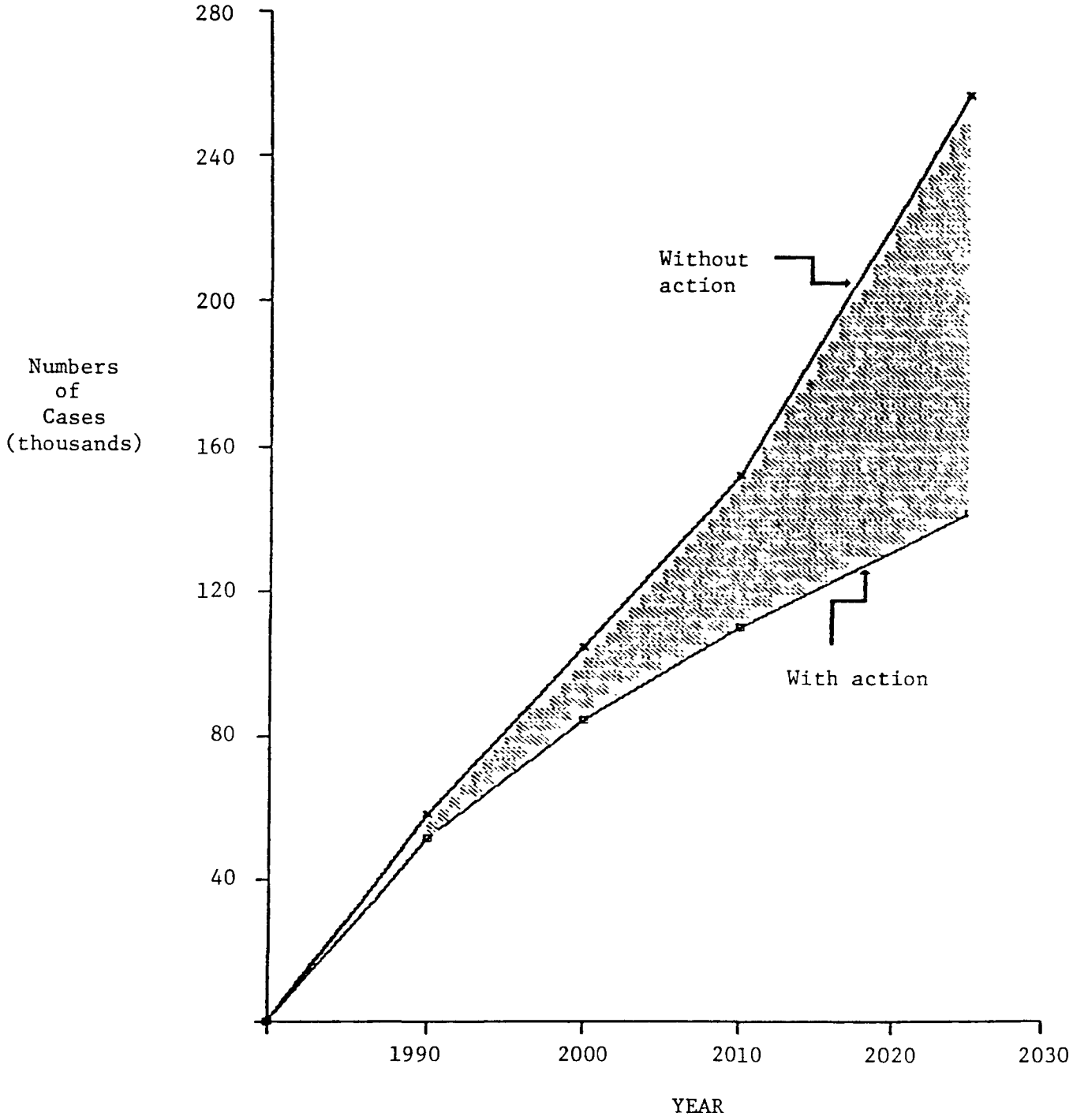

Figure 2. The Incidence of Skin Cancers in the United States Associated with Alternative Ozone Depletion Scenarios

Table 6. Effects of Global Average Ozone Depletion With Constant Emissions at 1980 Levels

		EFFECTS		
YEAR	OZONE DEPLETION	SKIN CANCERS[a] [% increase] Male/Female	U.S.[b] [new cases/yr]	PVC DAMAGE-U.S.[c] [millions of 1984 $/year]
1990	1.40%	5.6/ 4.2	51,900	5.0
2000	1.80%	7.2/ 5.4	84,800	7.0
2010	2.00%	8.0/ 6.0	110,600	8.0
2025	2.00%	8.0/ 6.0	141,900	8.0

a Based upon a 4x increase in the incidence of skin cancer for males and a 3x increase in incidence for females per unit depletion of ozone (Fears and Scotto 1983).

b Increase from a base level of 400,000 cases/yr.

c Interpreted from Andrady and Horst (Volume 2).

Table 7. Effects of Global Average Ozone Depletion With Continued Production Growth

		EFFECTS		
YEAR	OZONE DEPLETION	SKIN CANCERS[a] [% increase] Male/Female	U.S.[b] [new cases/yr]	PVC DAMAGE-U.S.[c] [millions of 1984 $/year]
1990	1.80%	7.2/ 5.4	58,900	7.2
2000	3.00%	12.0/ 9.0	104,800	11.0
2010	4.40%	17.6/ 13.2	152,500	17.5
2025	7.50%	30.0/ 22.5	256,400	35.0

a Based upon a 4x increase in the incidence of skin cancer for males and a 3x increase in incidence for females per unit depletion of ozone (Fears and Scotto).

b Increase from a base level of 400,000 cases/yr.

c Interpreted from Andrady and Horst (Volume 2).

Table 8. Difference Between Constant 1980 Emissions and Continued Production Growth Scenarios

	EFFECTS			
YEAR	OZONE DEPLETION	SKIN CANCERS [% increase] Male/Female	U.S. [new cases/yr]	PVC DAMAGE-U.S. [millions of 1984 $/year]
1990	0.4%	1.6/ 1.2	6,300	2.0
2000	1.2%	4.8/ 3.6	20,000	4.0
2010	2.4%	9.6/ 7.2	41,900	9.5
2025	5.5%	22.0/ 16.0	114,500	27.0

A less obvious category of effects include those generated as indirect consequences. For example, Whitten and Grey (Volume 2) present research indicating that increased levels of UV-B irradiance due to ozone depletion would stimulate increased formation of photochemical oxidants. Their results indicate that ozone concentrations would peak earlier in the day and at greater distances from the source, with the result that a larger human population would be exposed and at risk. EPA is currently assessing existing ozone standards in light of new research concerning general health effects. Further, as many as 24 cities across the nation will not be in compliance with existing standards by the December 30, 1987 deadline. Increasing levels of UV-B will definitely exacerbate this problem and increase substantially the magnitude of investment required to maintain urban air quality.

These effects are not limited to urban areas. Some of the most significant damages to date associated with increasing ambient ozone concentrations have accrued in agricultural areas. As described in the National Crop Loss Assessment (Adams and McCarl 1985; Garcia et al. 1986), yield reductions and the consequent impacts upon profitability have cost between $0.7 and $2.0 billion annually. Increases in the ambient concentrations of ozone in rural areas obviously would increase the extent of these damages. Whitten and Grey's results were extended to rural areas in an attempt to identify the possible magnitude of this impact. The increases for ground ozone concentrations in urban areas associated with different levels of ozone depletion from their research were applied to existing average rural ambient ozone concentrations. The resulting concentrations were evaluated for yield reductions by using the dose-response relations developed by Heck et al. These yield reductions for the "with action" and "without action" scenarios are shown in Tables 9 and 10.

Table 9. Indirect Effects of Global Average Ozone Depletion With Constant Emissions at 1980 Levels

YEAR	OZONE DEPLETION	CROP LOSS [a] % yield reduction			
		corn	wheat	soybeans	cotton
1990	1.40%	less than 1.0% for all crops			
2000	1.80%	"		"	
2010	2.00%	"		"	
2025	2.00%	"		"	

[a] Additional damages from dose response relations given in Heck et al.

Table 10. Indirect Effects of Global Average Ozone Depletion With Continued Production Growth

YEAR	OZONE DEPLETION	CROP LOSS [a] % yield reduction			
		corn	wheat	soybeans	cotton
1990	1.80%	less than 1.0% for all crops			
2000	3.00%	less than 1.0% for all crops			
2010	4.40%	0.45%	0.45%	1.20%	1.80%
2025	7.50%	1.50%	1.40%	2.80%	3.30%

[a] Additional damages from dose response relations given in Heck et al.

The results under controlled emissions show very slight effects throughout the period of analysis. The increasing depletion associated with continued emissions growth would cause reductions in soybean and cotton yields by the year 2010. These would be more pronounced by 2025. The differences in percentage yield reductions that could be attributed to policy action are displayed in Table 11. No attempt has been made to translate these yield reductions into an economic dimension because of the complex interaction of behavioral and market responses. The four crops examined are major commodities in the world's food and fiber system, as illustrated in Table 12. When aggregated across the immense acreages and values shown for these crops, even small changes would produce significant damages.

This paper has been modest in the costs that have been estimated. Table 13 provides an itemization of the effects identified at the EPA/UNEP conference which have not been included. Despite the lack of attention to this wider catalogue of effects, this analysis suggests that we have answered the question of whether to act. Even those effects about which we have great uncertainty represent incentives to action. Perhaps the most significant category of such uncertain impacts is that described as environmental effects. The changes stimulated by the direct and indirect effects of both increases in UV-B radiation and climate change will be most profound for natural ecosystems and their inhabitants. Consider, for example, the spatial shifts in agricultural production regions likely to occur from the combined stresses of increased UV-B and climate change. Soil moisture changes, direct yield reductions, changes in the temperature regimen, and enhanced carbon dioxide concentrations will alter comparative advantage. Production regions are likely to encroach on currently marginal lands devoted to wildlife habitat, forestry, and open space. The magnitude of these changes have the potential to eradicate the substantial investment that we have committed to maintaining species diversity and wildlands.

A caveat is in order: In valuing future outcomes, we are conditioned by current prices that reflect the existing pattern of resource and commodity availabilities. As population grows in the future and as increasing resources are devoted to maintaining the economic well-being of those future generations, the availability of natural resources and wildlands can be expected to decline. This change in physical supply can occur at exactly the time when demands for the nonconsumptive uses of such resources will be higher if current tasks and preferences endure. Consequently, they may be much more precious to future generations.

Our real dilemma in the evaluation of these alternative futures is the lack of a criterion by which to gauge them. In particular, policy formation is hampered by the lack of an acceptable ozone depletion management target framed in terms of public health and environmental systems damage. Until that target is set and its implications for allowable atmospheric chlorine concentrations, CFC growth, and use levels are calculated, we don't really know the potential implications of widely divergent alternative futures. Further, in the absence of a policy target for a maximum allowable ozone depletion, it is difficult to assess the importance of the uncertainties underlying the alternative long-term forecasts for CFCs. Recall that scientists have cautioned that "once the predicted change in climatology or ozone depletion diverges substantially from current conditions, the validity of the models becomes suspect." Consequently, what is needed is a decision concerning

Table 11. Difference Between Constant 1980 Emissions and Continued Production Growth Scenarios

YEAR	OZONE DEPLETION	CROP LOSS % yield reduction			
		corn	wheat	soybeans	cotton
1980	0.0%	0	0	0	0
1990	0.4%	-	-	-	-
2000	1.2%	-	-	-	-
2010	2.4%	0.45	0.45	1.20	1.80
2025	5.5%	1.50	1.40	2.80	3.30

Table 12. Principal Crop Commodity Statistics for 1984

CROP	WORLD ACREAGE	U.S. ACREAGE	U.S. CROP VALUE
	--- (thousands of acres) -----		(billions 1984$)
Cotton	85,067	10,380	3.66
Corn	312,299	80,434	20.50
Soybeans	130,646	67,735	11.40
Wheat	570,795	79,213	8.70

Source: Agricultural Statistics 1985, U.S. Government Printing Office, Washington, D.C., 1986.

Table 13. Effects of Ozone Depletion and Climate Change

HEALTH EFFECTS

Direct Effects of UV-B Radiation
- melanoma
- immune system suppression
- ocular damage

Indirect Effects of UV-B Radiation
- increased human exposure to increased air pollutants

Direct Effects of Climate Change
- temperature thresholds and increased mortality

Indirect Effects of Climate Change
- flooding severity from sea level rise
- increased frequency of severe weather

AGRICULTURAL EFFECTS

Direct Effect of UV-B Radiation
- crop yield reductions

Indirect Effects of UV-B Radiation
- changes in competitive balance between plant species

Direct Effects of Climate Change
- soil moisture changes
- changes in crop suitability

Indirect Effects of Climate Change
- comparative advantage and spatial location of production
- equipment complements
- chemical input use
- pest timing and impact
- property values and financial stress

FISHERIES EFFECTS

Direct Effects of UV-B Radiation
- phytoplankton mortality
- larval sensitivity

Indirect Effects of UV-B Radiation
- changes in species diversity
- endangered species
- reductions in commercial catch

MATERIALS DAMAGES

Indirect Effects of Climate Change
- coastal property inundation
- salt water intrusion
- erosion
- flooding

ENVIRONMENTAL EFFECTS

- species diversity
- endangered species
- pesticide, herbicide, trace element loadings
- habitat reductions
- wild and scenic rivers
- wetlands disappearance

acceptable public health and environmental impacts associated with alternative levels of stratospheric ozone depletion.

FUTURE RESEARCH NEEDS

It has become extremely fashionable to highlight the scientific uncertainties surrounding any particular environmental problem requiring public decisions to be made. As most of us know, uncertainty is a fact of life. Its new found vogue in the policy arena belies this normal human experience. For example, when making a corporate move, new housing is normally acquired. Such moves typically occur across steep housing gradients. In today's markets of rapidly appreciating prices and high demand, the potential buyer must be prepared to make quick decisions or be foreclosed on the possibility of making a decision. Business is not much different except the stakes are higher. Opportunities present themselves and then vanish. To continue the analogy, the business of running a global environment has even higher stakes. We, too, are presented with opportunities for action-decision making, which may never be offered again. To defer action when the opportunity arises could mean its irrevocable loss. So, there is uncertainty in the economic future of CFCs, uncertainty in the atmospheric science and effects, and uncertainty in the opportunities for decision making.

The best way to represent this problem of uncertainty is to view any policy action that might be taken as insurance. After all, the point to insurance is the opportunity to manage uncertainty and its attendant risks. Limiting the emissions of CFCs can be viewed as an insurance policy against the multifarious potential future damages that are explored by the authors of this report. What prudent person among us has not purchased insurance? The consequences of ozone depletion alone should cause us to act, but the possibility of preventing some of the global warming is further reason. Research is still needed but it should be focused. The following are some specific suggestions.

When one considers the potential consequences of climate change and ozone modification, the relative lack of research on ecological consequences is striking. Not only is the general level of funding for research in ecology extremely limited, but there is virtually no focus on the consequences of the anticipated changes for natural ecosystems.

Other ecological stresses have been explored in some detail. For example, we have begun to understand the response of freshwater ecosystems to acid deposition, and a rudimentary and fragmented picture is developing of the effects of air pollution stresses on mid-latitude forests. These efforts provide a good launching point for ecological studies of the consequences of climate change and ozone modification. There are two reasons for this argument. First, adequate baseline data for the relevant systems are being developed. Second, as Bruce (this volume) points out, the climate/ozone reduction stress will act synergistically on these systems with the acid deposition-air pollution stresses that are the focus of current studies.

A few examples illustrate this point. Mid-latitude forests that are stressed by air pollution in Central Europe experienced rather rapid declines after 1979. Some have suggested that this decline occurred as a natural climate stress (successive warm periods) was superimposed on a long term air

pollution stress. It is possible that this large, rapid change in forest status is a precursor to the effects of climate change, acting in combination with air pollution. One might suppose that this synergistic effect will accelerate the effect of climate change alone in altering forest distributions on the earth's surface. This particular synergy obviously links with the Whitten study; the enhanced ultraviolet flux from ozone modification will increase oxidant concentrations, which act as phytotoxins.

From a policy perspective, the interactive effects of these stresses are very important. By accelerating the consequences of climate change, they will put that stress in a current context, and signal large ecological changes sooner than otherwise expected. Timing becomes especially important if extreme temperature periods are ecologically significant because the number of such periods exceeding a given temperature will increase as climate changes. As an unfortunate consequence, heavily polluted areas become a testing ground for the effects of climate change. We would urge a mid-latitude forest "watch" as an ecological early warning area.

Both the nitrogen and the sulfur cycles will be affected by global warming, providing another set of synergisms and critical ecosystems. Clearly, we have massively disturbed these cycles, and will do so more in the future, without knowing either the implications or where we are headed. Increases in global nitrogen and sulfur deposition and the effects of such deposition are already measured. The interaction of these increases with climate change and enhanced ultraviolet flux should be an important research focus.

These interactions also underscore the linked nature of climate change and other air pollutant stresses both at their sources and at the effects levels. They emphasize the efficacy of strategies to limit trace gas emissions in general and add a note of urgency to such action. In a way, the effects are already upon us. We should slow them down and let our knowledge expand faster than the rate at which we're changing the earth.

CONCLUSIONS FOR POLICY

Before identifying the priority policy research needs that this summarizing exercise leaves us with, it is important to make a few observations. First, most discussions concerning ozone depletion focus on CFCs 11 and 12. It should be clear by now that we must include a wider range of ozone-depleting chemicals within our regulatory framework. The remainder of the commercially produced CFCs plus the halons should be included. The bromine contained within the halons is many times more effective at depleting ozone than the chlorine of CFCs. If only F-11 and F-12 are managed and other chemicals are produced for a mature market, we will not attain the desired objective of protecting the ozone layer. Furthermore, consider the implementation of the production capacity limit within the European Economic Community: In that setting, the cap is set to the sum of the nameplate capacities for the various existing production facilities. There are a number of swing facilities that primarily produce F-11 and F-12 but for a portion of the year also produce F-22. If the F-11 and F-12 production capacity limits were to become binding, then these facilities would be dedicated to F-11 and F-12, and a F-22 facility could be constructed, adding more CFC emissions. We need a consistent and reliable method of adding these different chemical compounds

together to ensure that their individual depleting effects are accounted for in any policy.

We need to identify an internationally and environmentally acceptable limit to stratospheric ozone depletion. Is the intent to limit the rate of growth of CFCs or is it to constrain the ultimate quantity discharged to the atmosphere? While we may perceive ourselves to be currently constrained in our ability to either articulate or implement any policy objective, we should actively assess the consequences of the possible choices. What if CFCs are not best conceived as a mature or saturated market? What are the effects of differences in policies, timing and force? If we delay policy action, will policy action in the future be more difficult? Delaying would not provide the needed stimulus for research into substitutes or reduced emission technologies. What are the opportunity costs of deferring control? To address these policy questions and deliver information to a rational policy process, we need to focus our research resources in the next year on the articulation of our uncertainty and its explicit incorporation into policy analysis. What are the consequences of being wrong and what is the least risky alternative? The real challenge is the design of policies to limit CFC emissions with associated monitoring and enforcement components that will protect the environment and yet allow all nations to share in the benefits of the use of these chemicals.

It is important to distinguish between irreversible decisions and irreversible actions. In the case of stratospheric ozone, an irreversible action is depletion and its attendant effects which cannot be undone except with the passage of very long periods of time. By contrast, policy actions to limit the growth in emissions of CFCs and other ozone-depleting substances do not represent irreversible decisions. Any agreement can be reconsidered and changed. The critical point is the irreversibility of the consequences, which represent an imperative quite distinct from whether policy may be reassessed and changed. This places the policy question before us strictly in the form of trading off short-term economic advantages for an environment that can be sustained in the long run.

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